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ELECTRICAL ENGINEERING RESEARCH LABORATORY
ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS

QUARTERLY PROGRESS REPORT

on

RESEARCH STUDIES ON PROBLEMS
RELATED TO ANTENNAS

Quarterly Report No. 3

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Aeronautical Systems Division

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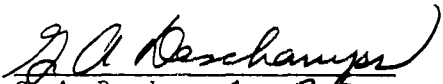Project Engineer - James Rippin - ASRNCF-3
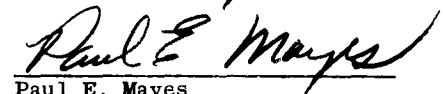

25 June 1963

Report for the Period: Approved by:

1 March 1963

                                                G. A. Deschamps
        to   Professor

31 May 1963

                                                Paul E. Mayes
                                                Associate Professor

Electrical Engineering Research Laboratory
Engineering Experiment Station
University of Illinois
Urbana, Illinois

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1. RADIATION FROM PERIODIC STRUCTURES

1.1 Purpose

The purpose of this investigation is to explain the observed properties of log-periodic antennas through experimental and analytical investigation of their uniform periodic counterparts.

1.2 Factual Data

1.2.1 Research Staff - P. G. Ingerson, P. E. Mayes

1.2.2 Status

Additional near field measurements have been made at frequencies in the "stopband" (complex wave region) on the uniform periodic dipole array. It is believed that some of the complex interference patterns which have been observed can be explained in terms of several waves existing simultaneously on the structure. Attempts are being made to correlate these waves with the several modes obtained in the calculations performed by Mittra and Jones*. Agreement between calculations and results measured previously in the passbands of the structure agree quite well. The "stopband" region is of considerable interest, however, since it is in this frequency range that backfire patterns are obtained.

1.3 Plans for the Next Interval

Determination of a more complete k-β diagram for the uniform periodic dipole array will be continued. Preparation of a technical report will be started.

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*R. Mittra and K.E. Jones, "Theoretical Brillouin (k-β) Diagrams for Monopole and Dipole Arrays and Their Application to Log-Periodic Antennas", Tech. Report No. 70, Contract No. AF33(657)-10474, Antenna Laboratory, University of Illinois, Urbana, Illinois, April 1963.

2. LOG-PERIODIC CAVITY-BACKED SLOT ANTENNAS

2.1 Purpose

This work is being directed toward the development of a log-periodic array of cavity-backed slots which will produce vertically polarized radiation without having the structure projecting above the ground plane.

2.2 Factual Data

   2.2.1 Research Staff - V. A. Mikenas and P. E. Mayes

   2.2.2 Status

As noted in previous reports this project is being developed on the basis of achieving a dual of the successful dipole array. In this way it should be possible to find a successful flush-mounted cavity-backed slot array which would produce vertically polarized backfire radiation in a frequency-independent manner.

The cavity array, including the feed system, was constructed as shown in Figure 2.1. The characteristic impedance of the printed circuit feed of the individual loops was designed for 300 ohms. This rather high value was chosen with the idea of obtaining a better match to the high input impedance of the individual cavity. The transmission line feeding the various loops was also designed for 300 ohms to feed against the ground screen. The loops were transposed in each cavity so that the required 180° phase shift was obtained between adjacent cavities to produce successful backfire radiation. The printed circuit feed was extended above the ground screen a distance of 1 in. in order to produce the least amount of discontinuity in the feed system. The total length of the printed circuit feed was designed such that the frequency at which the input impedance was purely resistive corresponded approximately to the resonant frequency of the cavity. This is only an approximate solution since mutual coupling between adjacent cavities produce perturbations which cannot be taken into account exactly. Having decided upon a length for a particular loop feed and cavity, the other loops were scaled proportionately by the scale factor τ ($\tau = 0.85$). In this scaling, all dimensions were scaled so that the characteristic impedance of the loop feed remained constant and the loop diameters were properly scaled for each cavity. The loops were then inserted and connected in series as implied by duality of the log periodic dipole array.

Impedance measurements were made and the first results are shown on the Smith Chart in Figure 2.2. Impedance measurements were taken from 300-1900 Mc although the
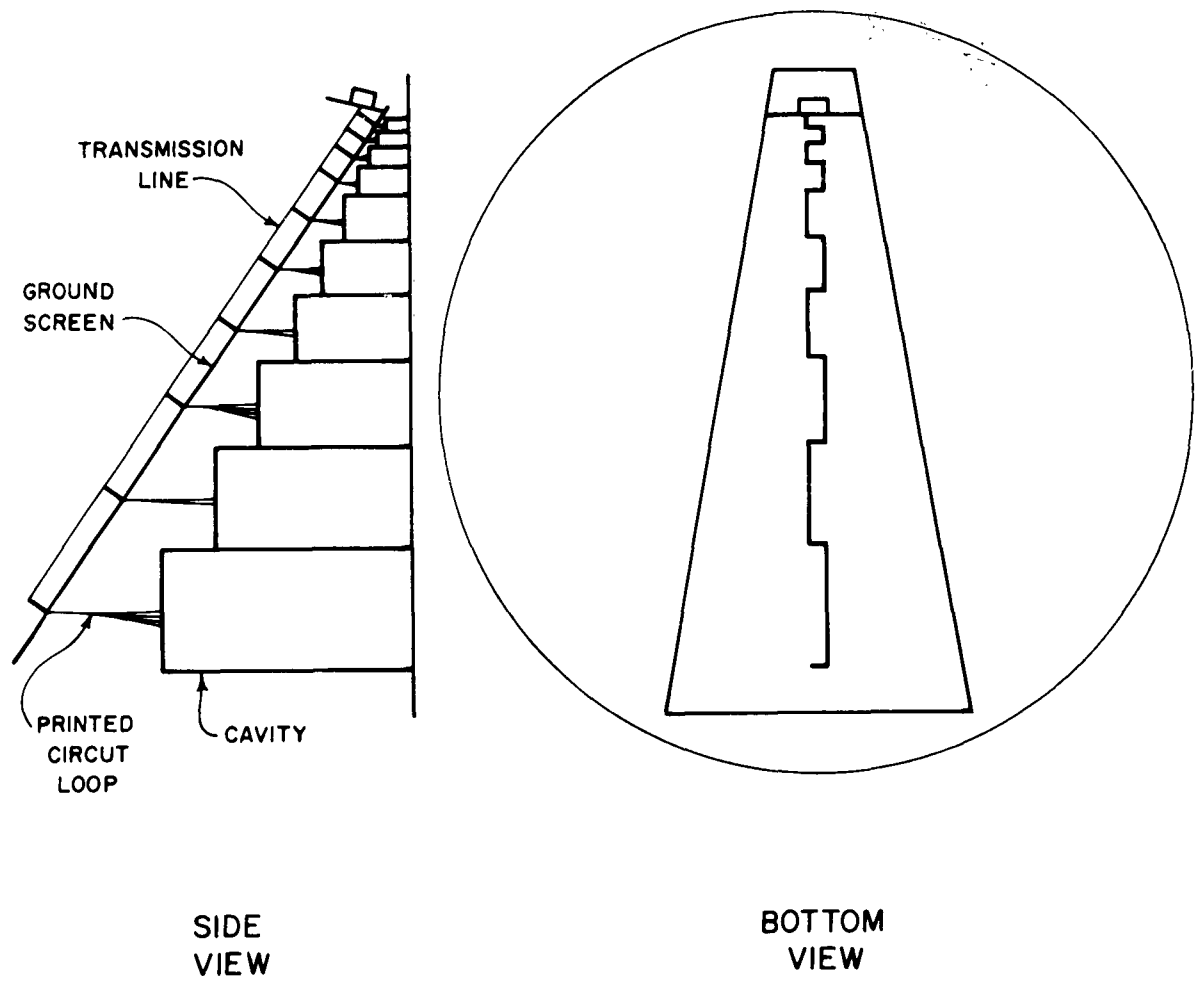
3

TRANSMISSION
LINE

GROUND
SCREEN

PRINTED
CIRCUT
LOOP

CAVITY

SIDE
VIEW

BOTTOM
VIEW

Figure 2.1. Cavity-Backed Slot Antenna with Feed System

4

Figure 2.2. Impedance Locus Versus Frequency in MC Referred
to 50 ohms

expected operating range was approximately 450-1500 Mc. The impedance points are not widely scattered, but indicate a rather high average value. Far field patterns were also measured and it was found that in the frequency range 450-1700 Mc, all patterns were either backfire or bi-directional, but mostly backfire. A number of patterns for several frequencies is shown in Figure 2.3. All patterns were taken in the H-plane. In order to investigate further the cause of the bi-directional patterns of the array near field plots were made. Some of these results are noted in Figure 2.4 with the pattern at the same frequency. It is shown there that the bi-directional pattern is accompanied by large field at the end of the antenna, i.e. end effect. It was noted that some correlation was found between the active region and the resonant frequency of the cavities. It was found at most frequencies the active region was located at a point corresponding to the cavity which was at resonance at that particular frequency. This is not an exact result but is approximately true. A great many more careful measurements would have to be taken to obtain more precise conclusions. The near field plots were obtained with a loop probe located approximately 4 cm away from the top of the cavity array. At some frequencies, however, the field was not reduced to negligible values at the end of the antenna. At these frequencies the patterns were generally bi-directional.

Although these results are encouraging, it seems that better performance might be attained if it were, in some way, possible to couple more energy into the cavities. This might be accomplished in one of several ways. From the near field plots, we have an idea where the active region lies and, consequently, it may be possible to tune the cavity in such a manner that it may match more closely the cavity or cavities in the active region. Another possibility would be to decrease the characteristic impedance of the transmission line feeding the printed circuit loops.

2.3 Plans for the Next Interval

It will be attempted to couple more energy into the cavity array by using some techniques such as those mentioned above. Plans are being made to build another cavity array of slightly different parameters but still keeping a rather low value of τ to correspond to values used in the log-periodic dipole array. In addition, a uniform periodic cavity array may be constructed to obtain the Brillouin diagram for the structure.
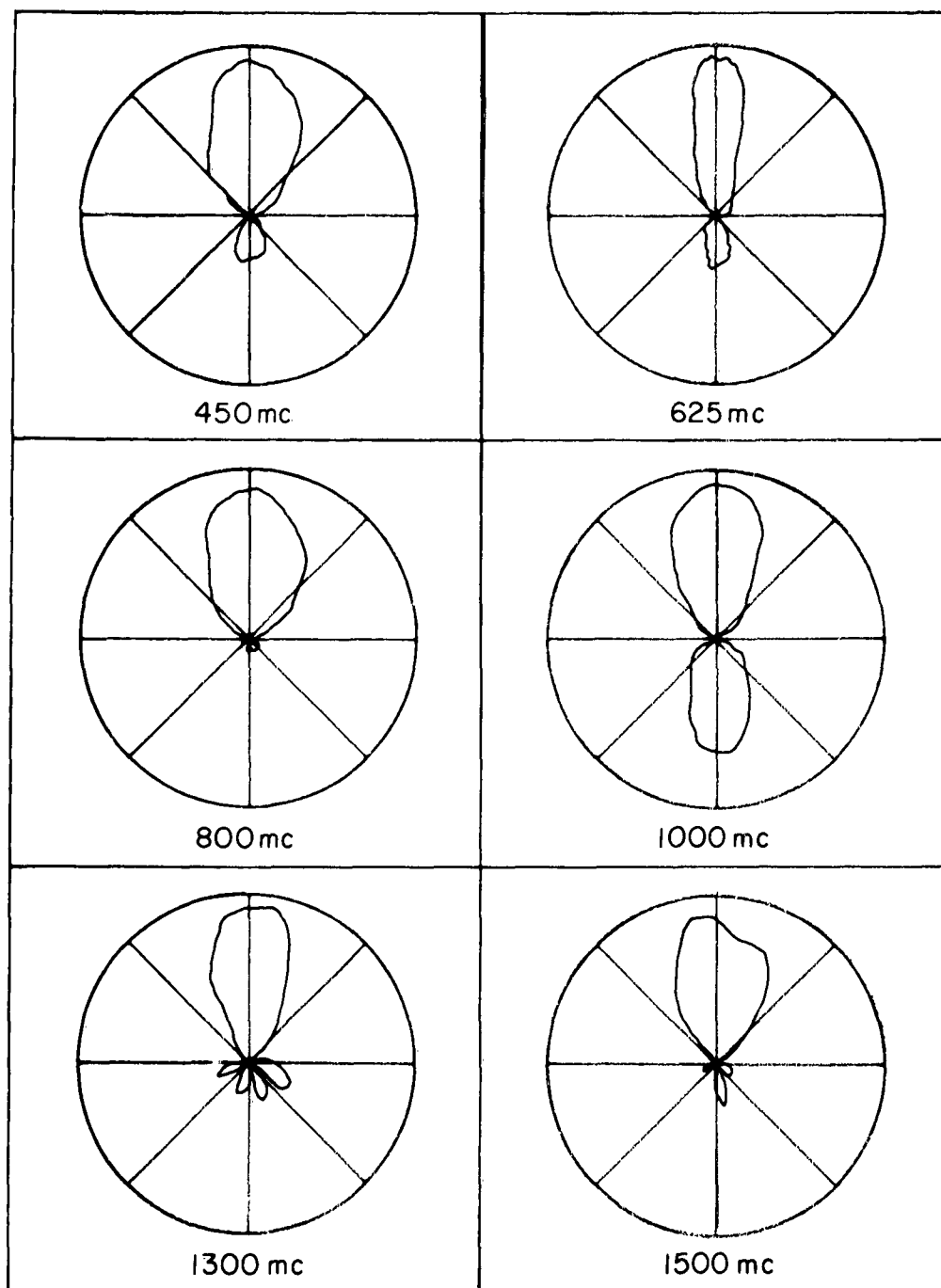
Figure 2.3. H-Plane Patterns of the Cavity-Backed Slot Antenna

FIELD AMPLITUDE

15 db

625 mc

H-PLANE PATTERN

FIELD AMPLITUDE

20 db

800 mc

H-PLANE PATTERN
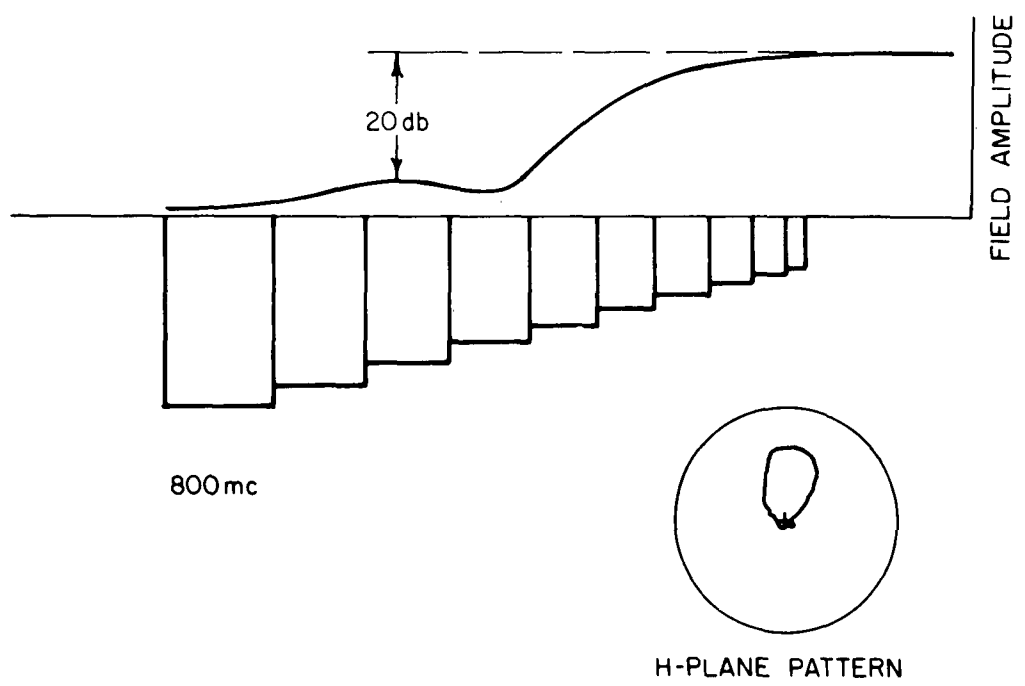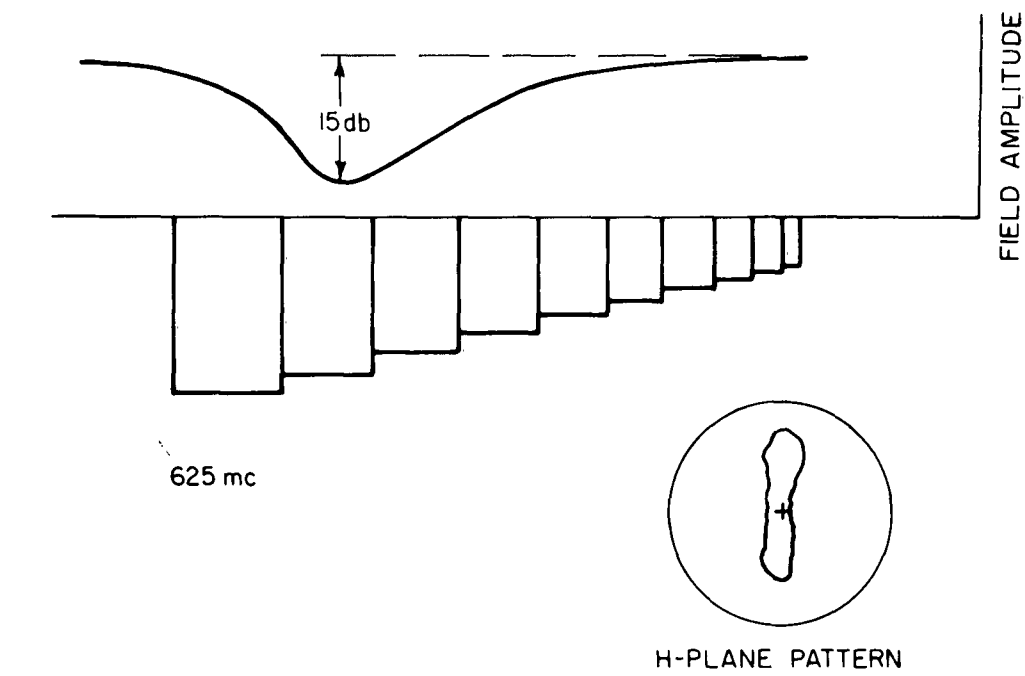
Figure 2.4.   Near Field Plots for 625 Mc and 800 Mc

3. LOG-PERIODIC MAGNETIC CURRENT ANTENNA

3.1 Purpose

The purpose of this work is to investigate an LP array of magnetic dipole elements.

3.2 Factual Data

3.2.1 Research Staff - P. E. Mayes

3.2.2 Status

A new model (CMCA-1-3) of the conical slot antenna was constructed with 16 cells as compared with 9 cells in the antenna (CMCA-1-2) reported in the previous Quarterly Reports Nos. 1 and 2. Otherwise the parameters of the antenna remain unchanged ($\tau = 0.89$, $\theta_o = 15^{\circ}$). It was expected that CMCA-1-3 would have an extended pattern and impedance bandwidth compared with CMCA-1-2. The measured patterns of CMCA-1-3 did indeed retain a smooth unidirectional shape to higher frequencies than CMCA-1-2 as shown in Figure 3.1. (Patterns of CMCA-1-2 were published in Quarterly Report No. 1). However, there were several frequency bands between the low and high-frequency cutoffs where the patterns were distorted. The measured impedance of CMCA-1-3, normalized to 300 ohms, is shown on the Smith Chart in Figure 3.2. There is good correlation between the frequencies where the VSWR is low in Figure 3.2 and the frequencies of good patterns in Figure 3.1.

3.3 Plans for the Next Interval

Additional comparative tests will be made on CMCA-1-2 and CMCA-1-3 in an attempt to determine what has caused the deterioration in performance when going to extended length. A different feed system will be tried first of all, since the construction of the two antennas is almost identical in all other respects.
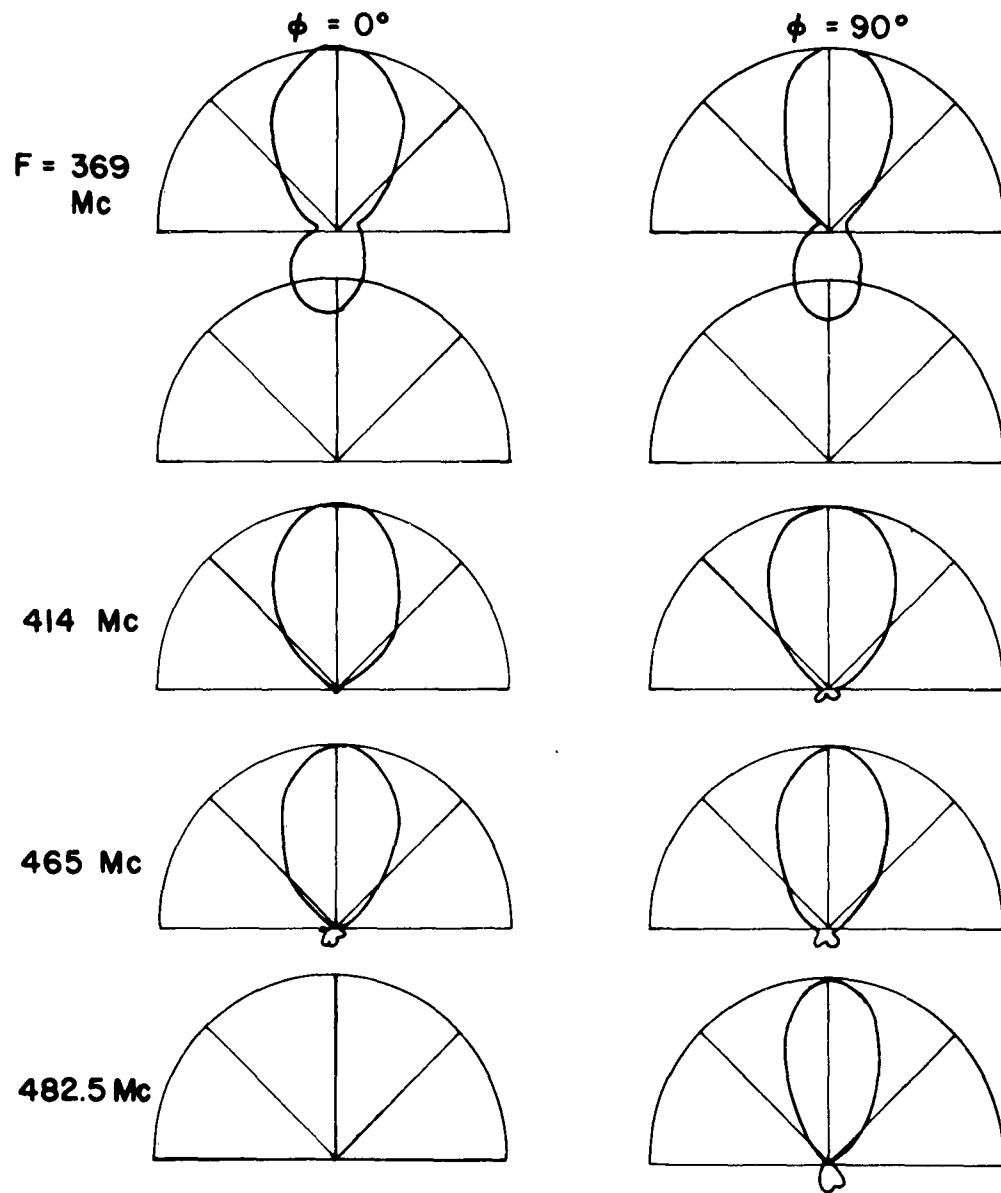
Figure 3.1a. Radiation patterns of the log-periodic conical
slot array, CMCA-1-3.
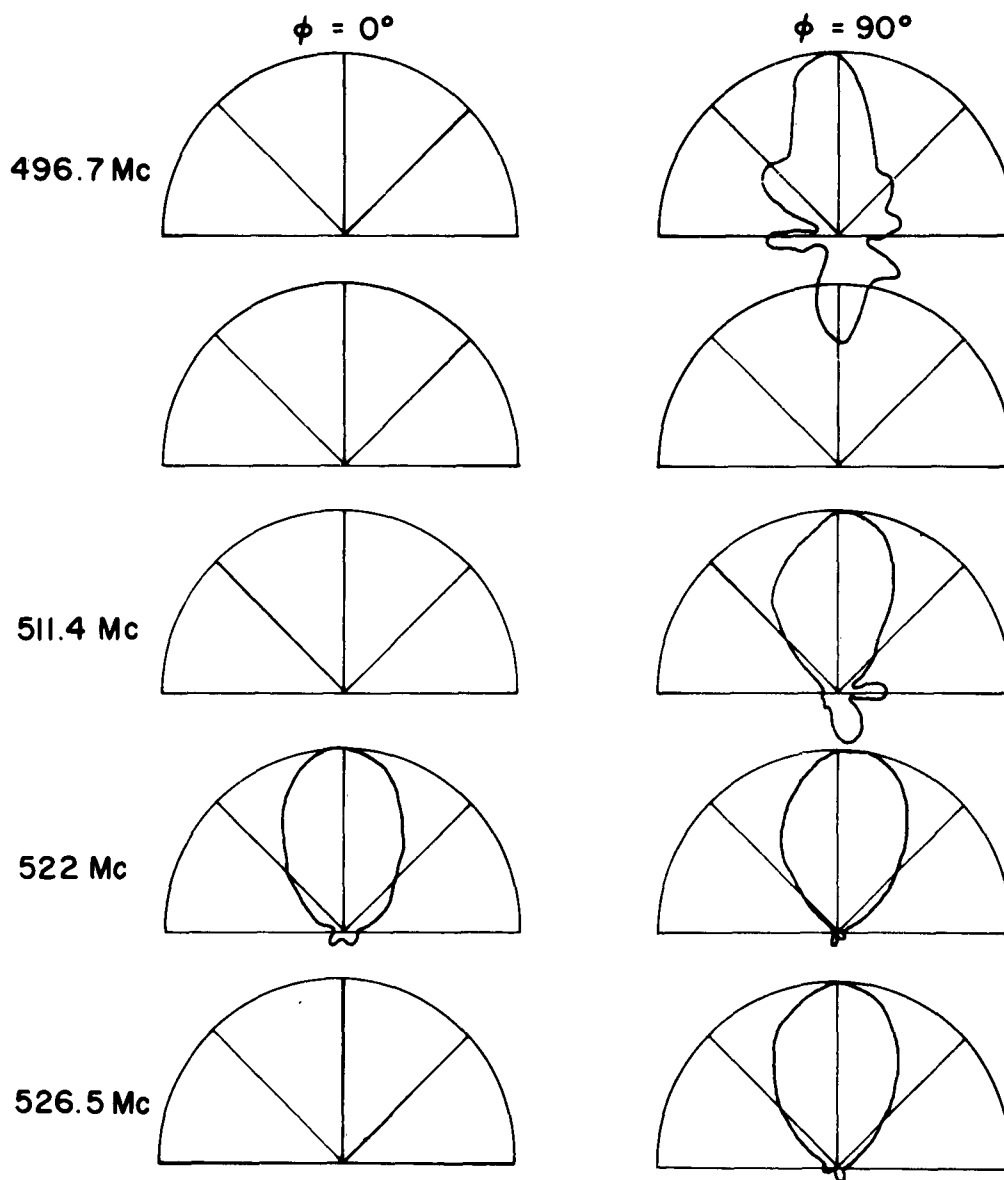
Figure 3.1b. Radiation patterns of the log-periodic conical
slot array, CMCA-1-3.
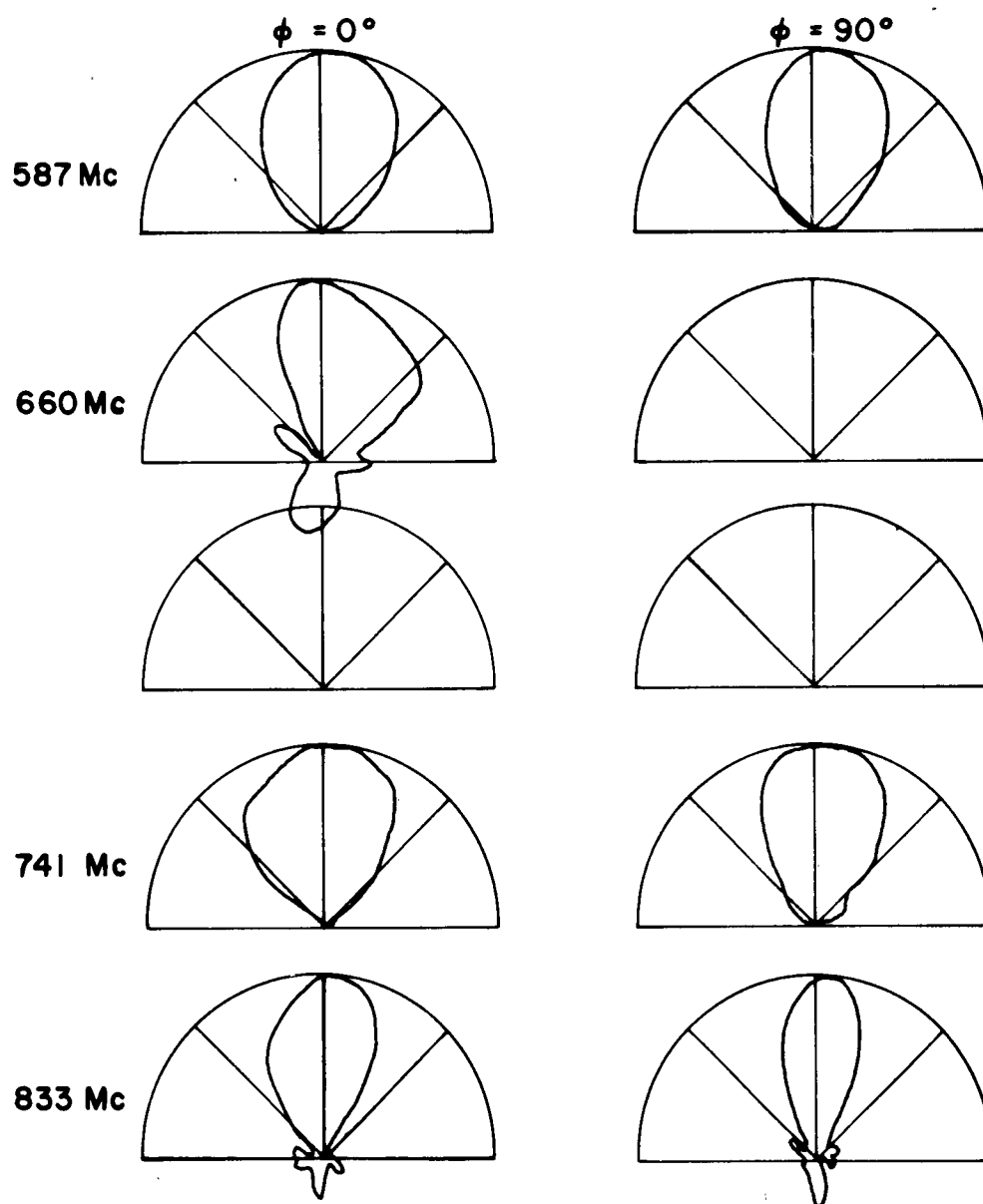
Figure 3.1c. Radiation patterns of the log-periodic conical
slot array, CMCA-1-3.

$\phi = 0°$ $\phi = 90°$

875 Mc

936 Mc

1052 Mc

1181 Mc
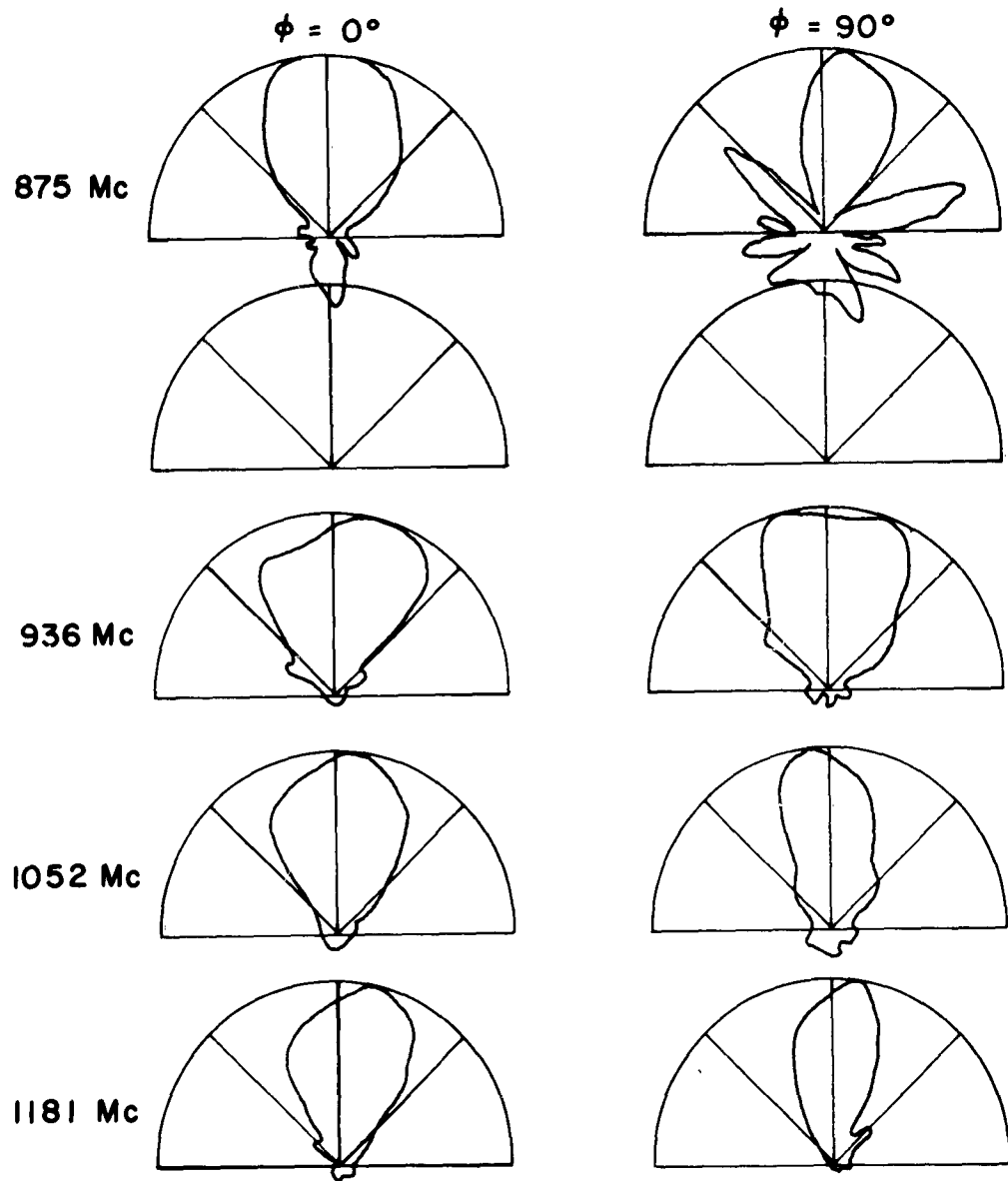
Figure 3.1d. Radiation patterns of the log-periodic conical
slot array, CMCA-1-3.
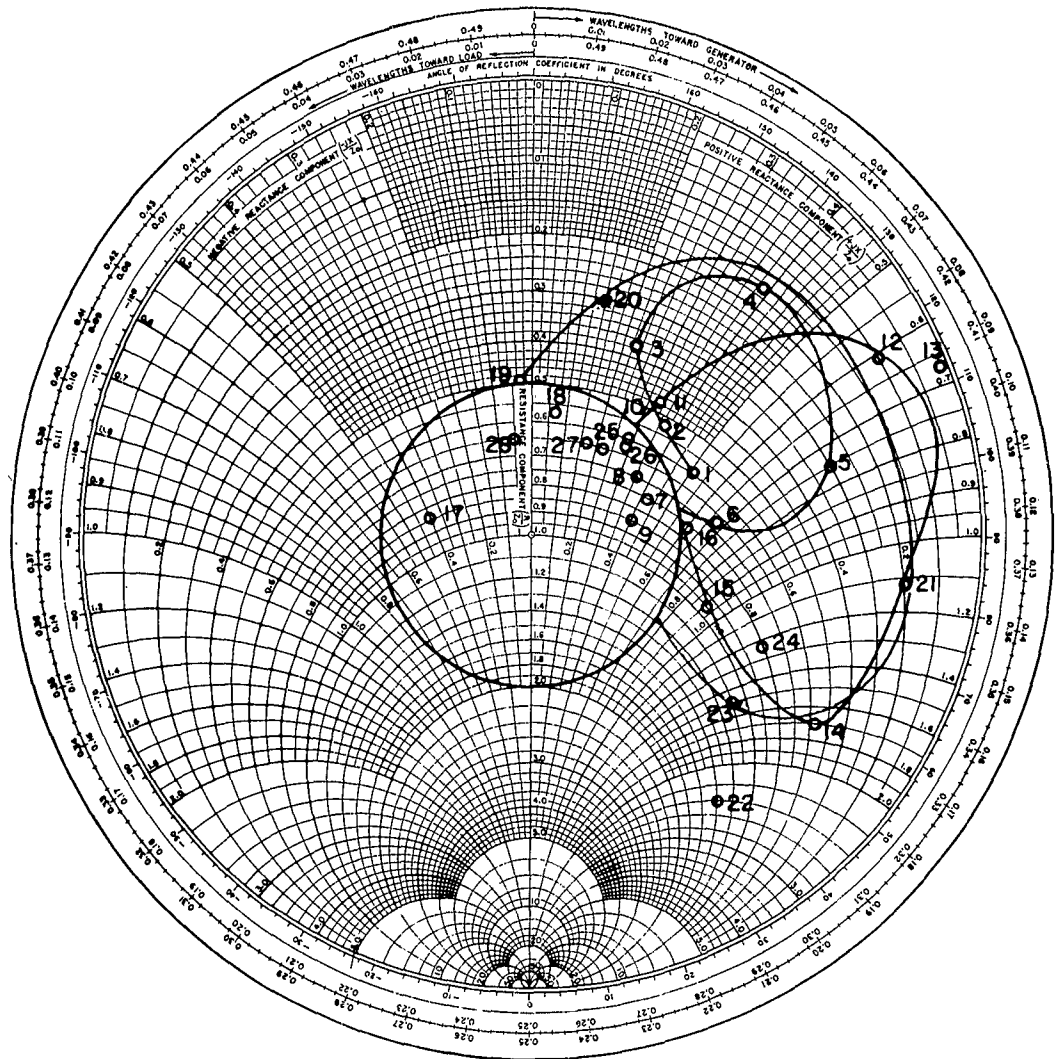
Points	Frequency	Points	Frequency	Points	Frequency
1	350	10	455	19	609.2
2	360.4	11	468.5	20	627.2
3	371	12	482.5	21	645.8
4	382	13	496.7	22	665
5	393.3	14	511.4	23	684.6
6	405	15	526.5	24	704.9
7	417	16	542.1	25	725.7
8	429.3	17	558.2	26	747.2
9	442	18	591.7	27	769.3
				28	792.1

Figure 3.2. Measured impedance of log-periodic conical slot array, CMCA-1-3, referred to 300 ohms.

4. LOG-PERIODIC ZIGZAG ANTENNAS

4.1 Purpose

This work is directed toward obtaining design information about a class of periodic leaky wave structures which are potentially high-gain, frequency-independent antennas.

4.2 Factual Data

4.2.1 Research Staff - P. E. Mayes

4.2.2 Status

Two new models designated LPZZ-4 were built and tested during this quarter. Both have $\tau = 0.9$, $\alpha = 5^O$, $\beta = 3^O$, $\psi = 10^O$. One (LPZZ-4I) was constructed to operate from about 350 Mc up so that accurate impedance measurements could be made using it. The other (LPZZ-4P) was built to take radiation pattern tests above 1000 Mc.

Typical patterns recorded from LPZZ-4P are shown in Figure 4.1. They show a well-formed backfire beam with a backlobe which becomes negligible above 1100 Mc. The 3-db beamwidths in E and H plane are both approximately 40 degrees from 1000 to 2400 Mc. It should be noted that there is some beam tilt in evidence in these patterns. Since this might be caused by inaccurate construction, a series of patterns was also measured on the larger LPZZ-4I. Comparable E-plane beam scanning was observed in these tests also. The magnitude of these oscillations appears to be dependent upon the pitch angle of the zigzag. LPZZ-4 has a pitch angle of 22 degrees, the largest of any log-periodic zigzag tested to date. For comparison Figure 4.2 shows patterns for LPZZ-10 ($\tau = 0.9$, $\alpha = 10^O$, pitch angle = 10°). These patterns show very little beam swing, the beam being particularly stable at the lower frequencies. LPZZ-10 was constructed with cable arms. Considerable care was taken to insure that equal lengths of cable were used in the two arms.

The impedance of LPZZ-4I as measured on the 300 ohm Lecher wires is plotted in Figure 4.3. The pattern of points is similar to those measured on other LPZZ models. The majority of the points lie on the capacitive reactance side of the chart. The antenna is well matched to a 300 ohm line over most of the band from 350 to 1320 Mc. The maximum VSWR observed over this band was 2 8 at 1023.3 Mc. The mean impedance is 375-j15 ohms and the VSWR with respect to this value is less than 2.4.

4.3 Plans for the Next Interval

The pattern model, LPZZ-4P, has been rebuilt in an attempt to correct the assymmetry in the H-plane which was observed in the patterns of Figure 4.1. The dependence of beam swing upon pitch angle will be investigated further.

1000 Mc

1100 Mc

1200 Mc

1300 Mc
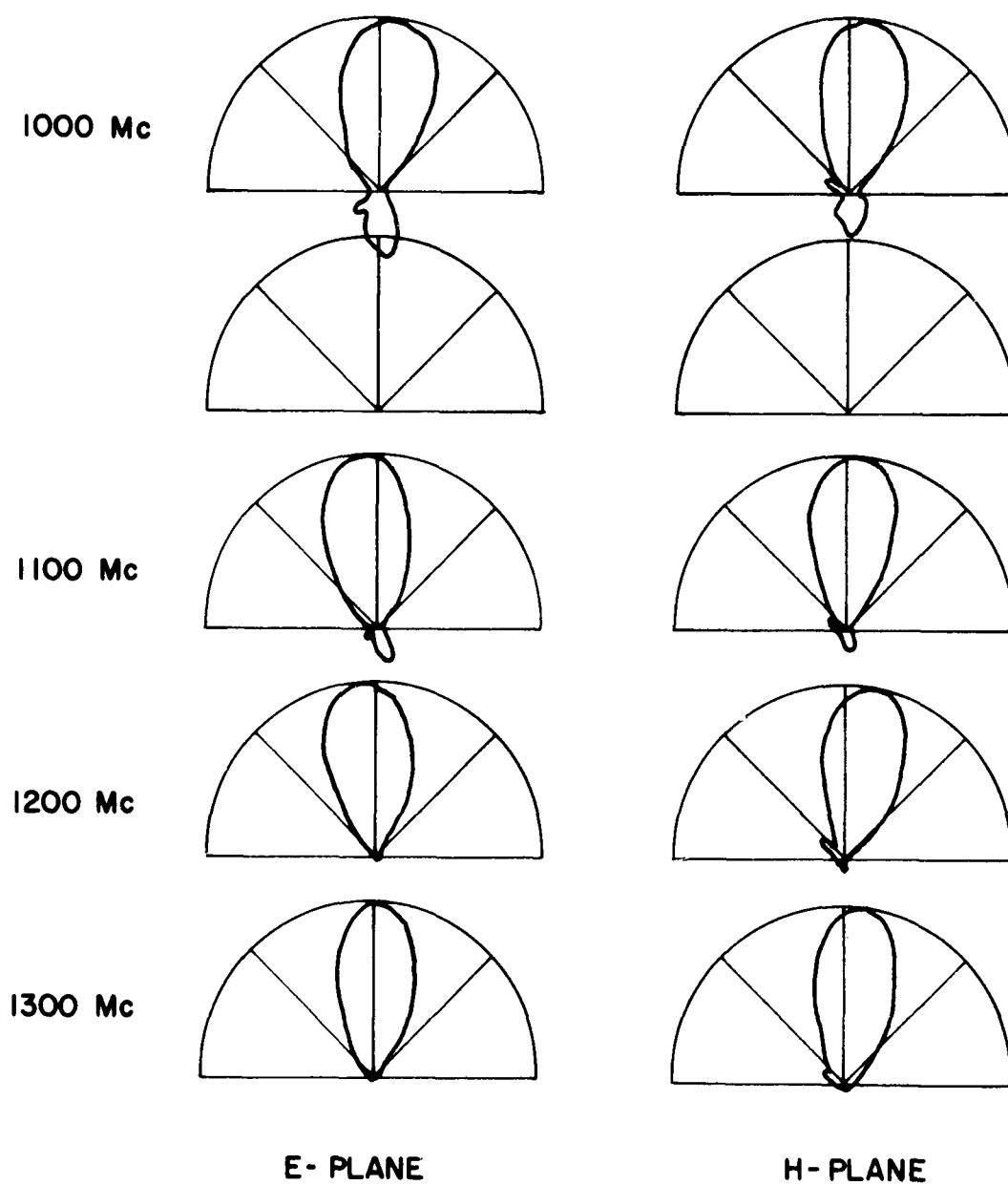
E- PLANE

H- PLANE

Figure 4.1a. E- and H-plane patterns of LPZZ-4.

1400 Mc

1500 Mc

1600 Mc

2100 Mc

2200 Mc
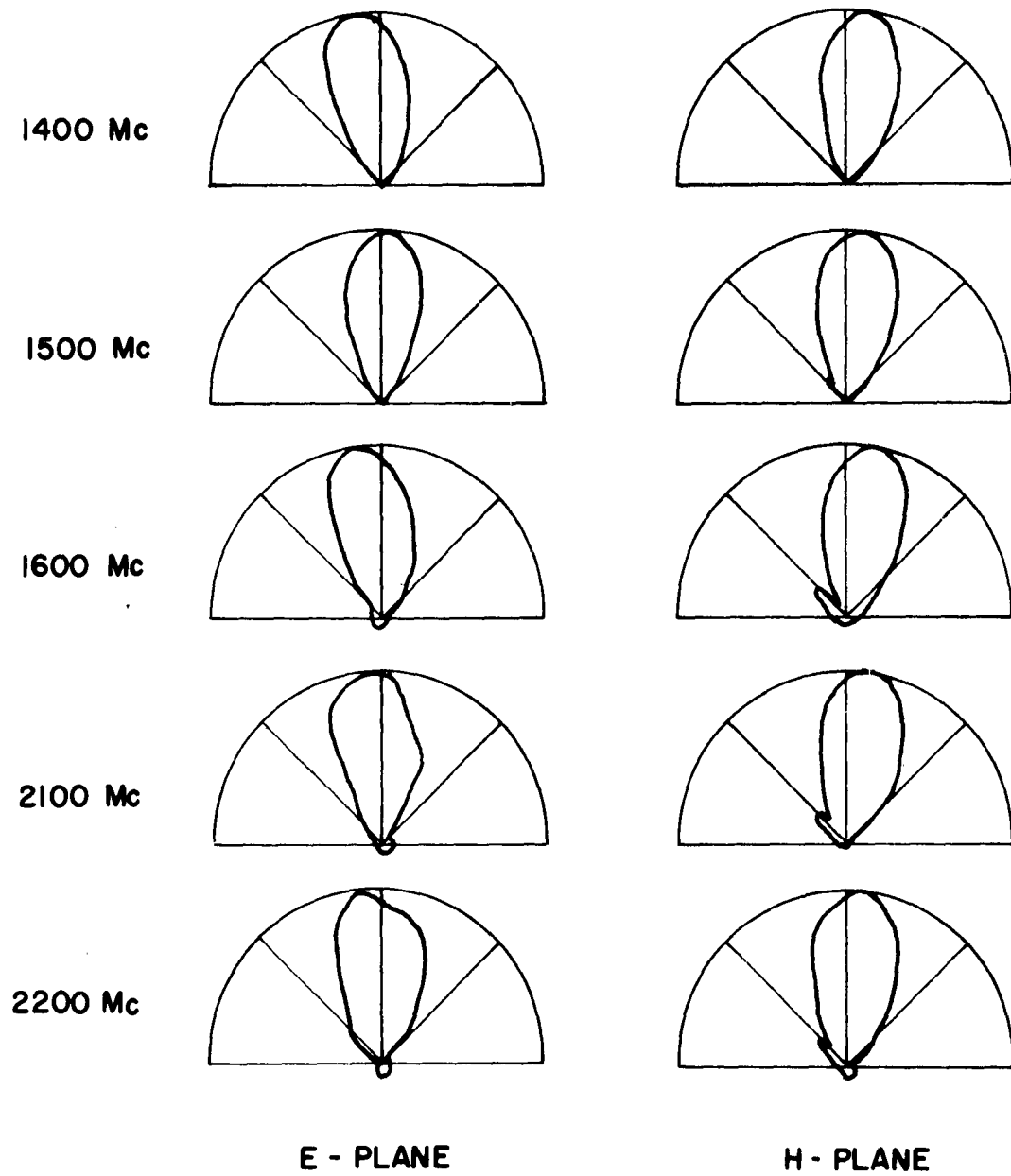
E - PLANE   H - PLANE

Figure 4.1b. E- and H-plane patterns of LPZZ-4.

2600 Mc
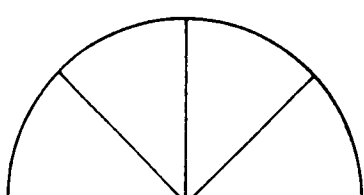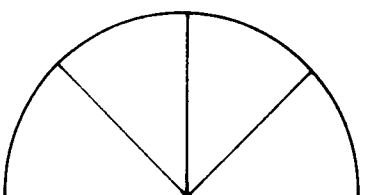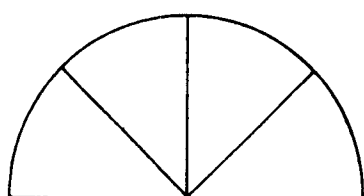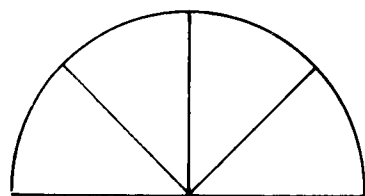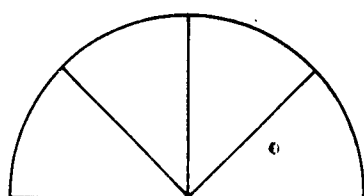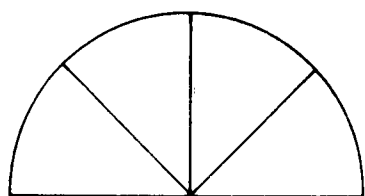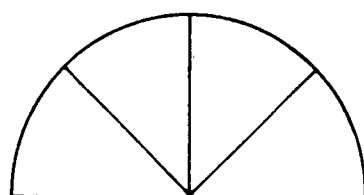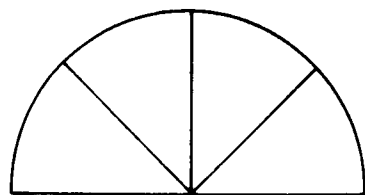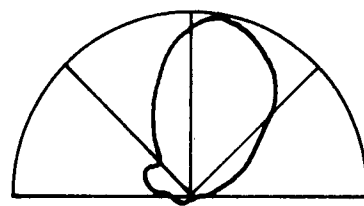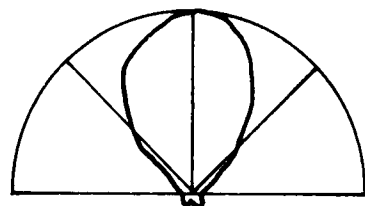
E - PLANE

H - PLANE

Figure 4.1c.   E- and H-plane patterns of LPZZ-4.

700 Mc

800 Mc

900 Mc

1000 Mc

1100 Mc
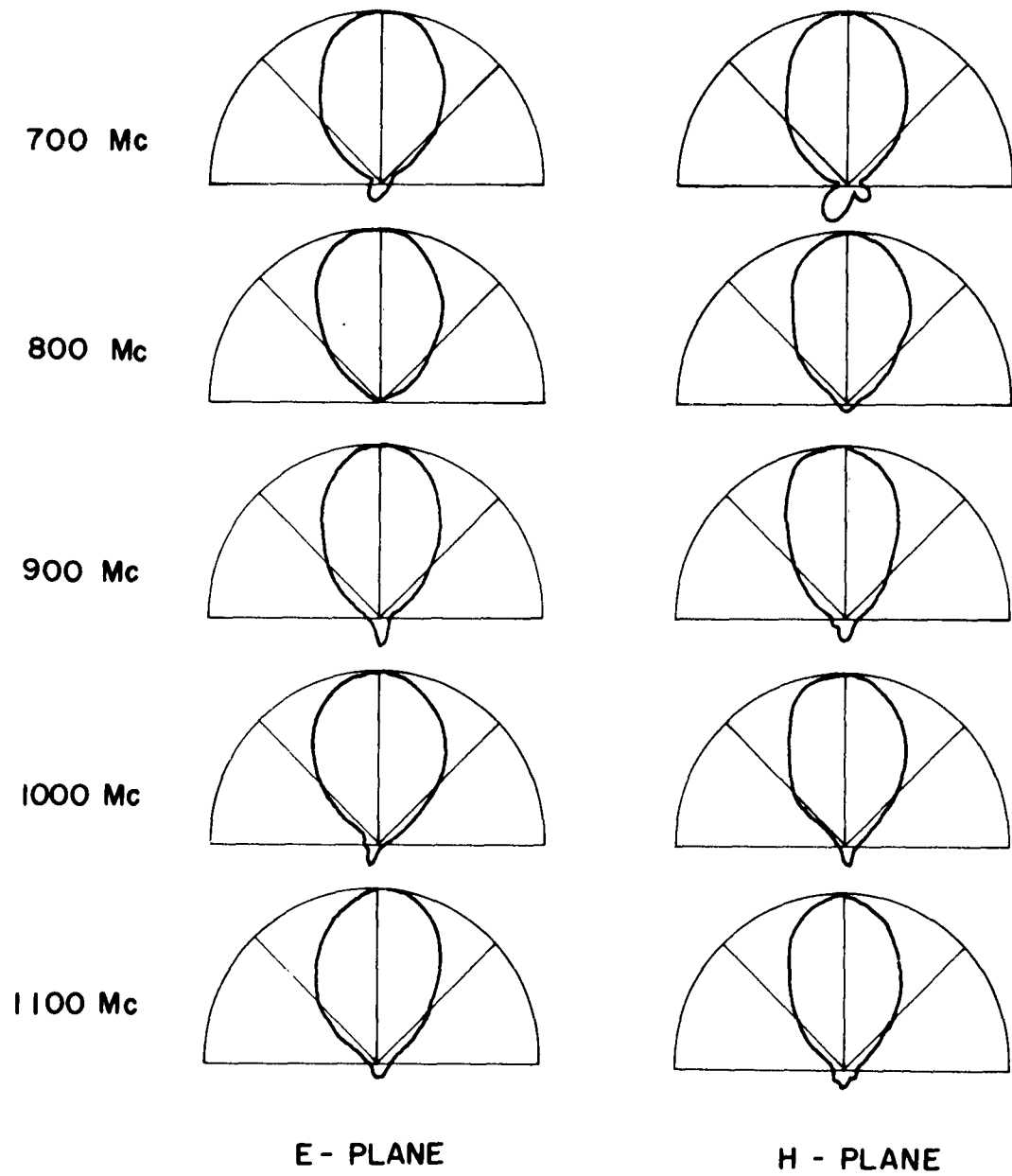
E - PLANE

H - PLANE

Figure 4.2a. E- and H-plane patterns of LPZZ-10.

1200 Mc

1300 Mc

1400 Mc

1500 Mc

1600 Mc
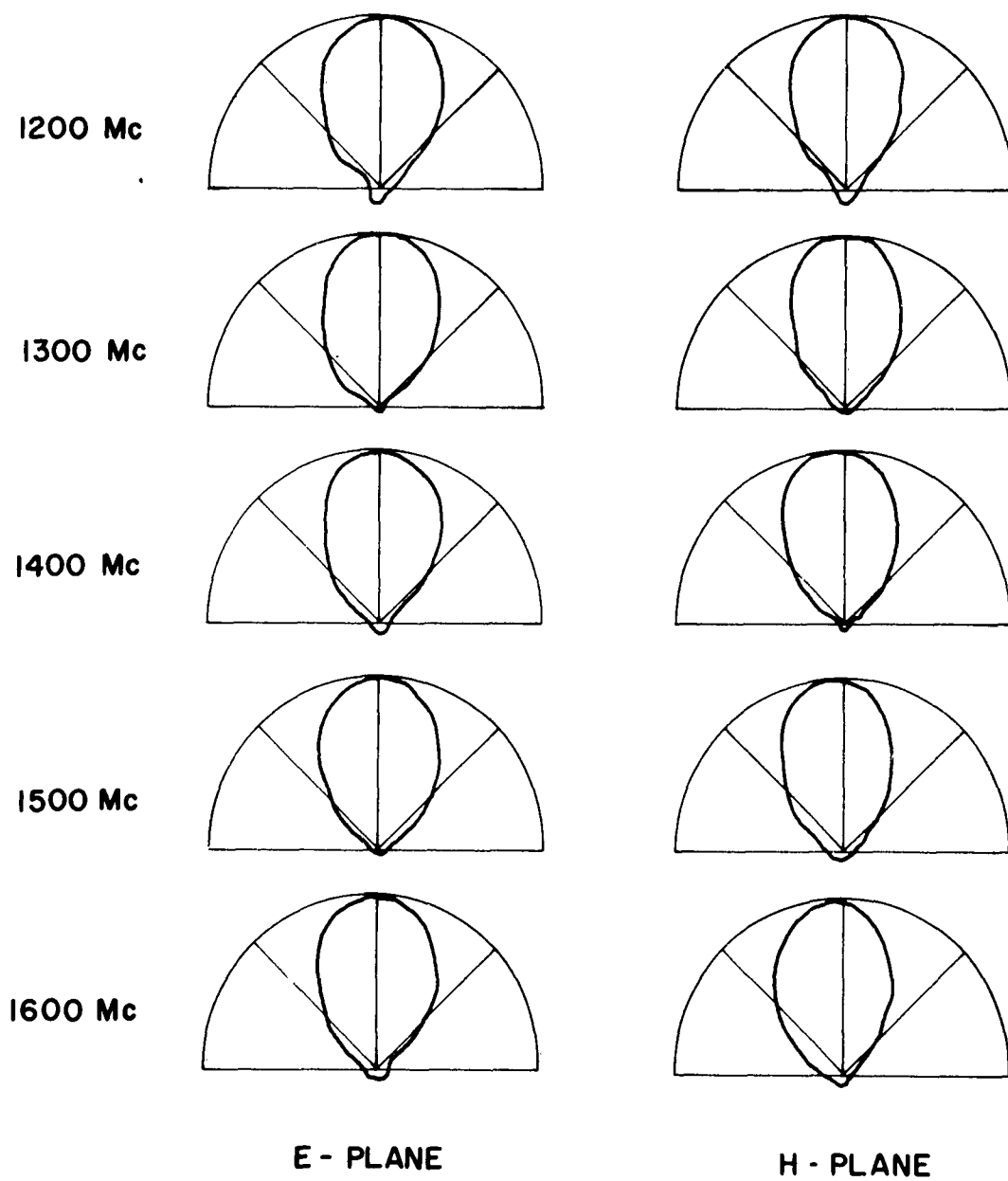
E - PLANE

H - PLANE

Figure 4.2b. E- and H-plane patterns of LPZZ-10.

1700 Mc

1800 Mc

2000 Mc

2200 Mc

2400 Mc
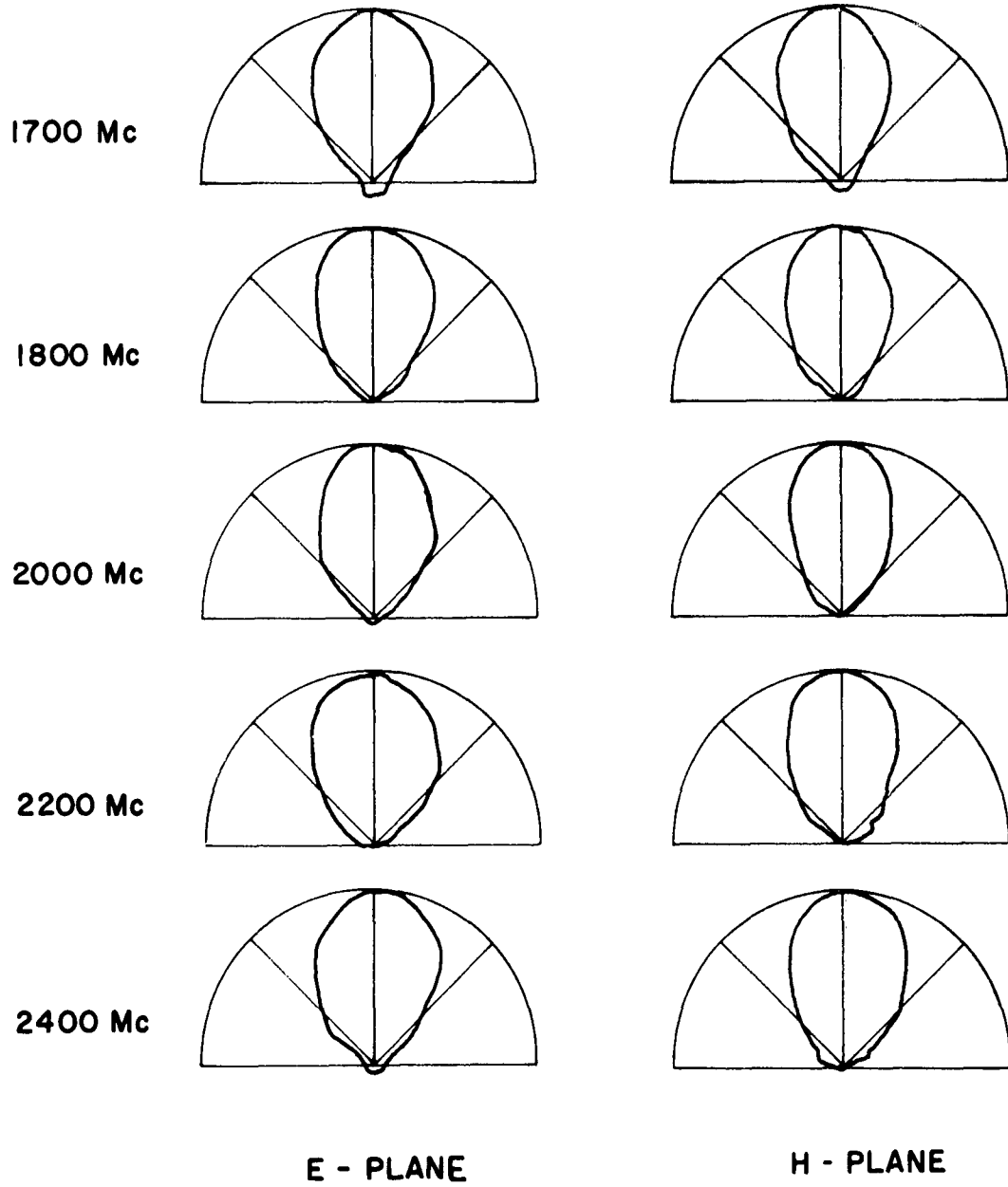
E - PLANE

H - PLANE

Figure 4.2c. E- and H-plane patterns of LPZZ-10.

2400 Mc
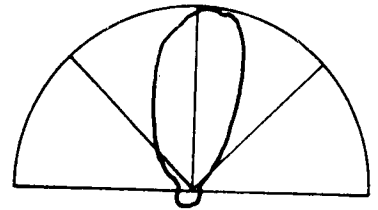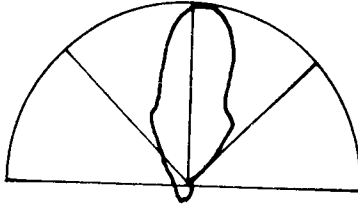
2600 Mc
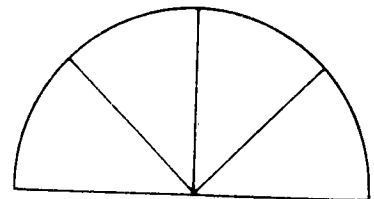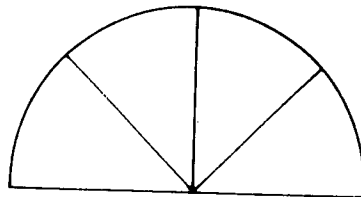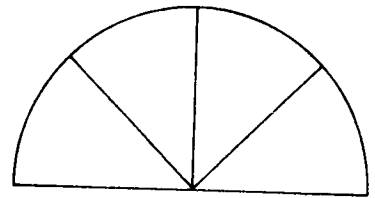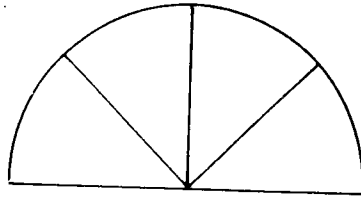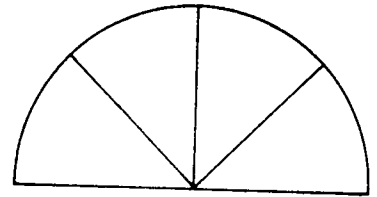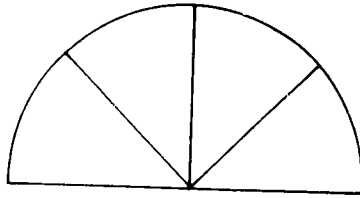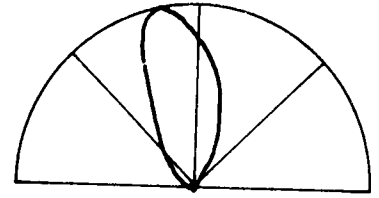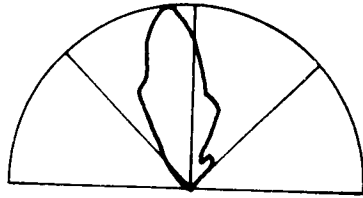
E - PLANE

H - PLANE

Figure 4.2d. E- and H-plane patterns of LPZZ-10.
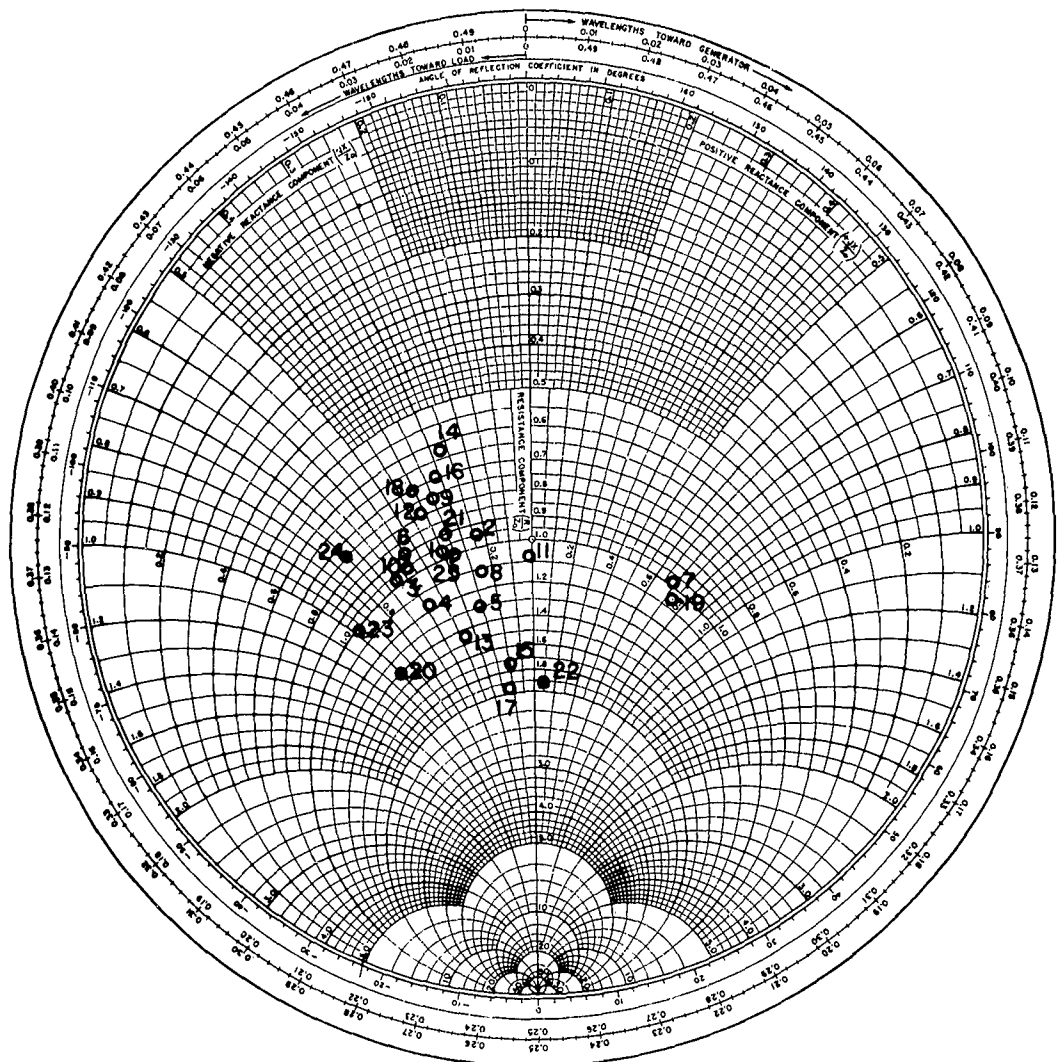
Points	Frequency	Points	Frequency	Points	Frequency
1	350	9	532	17	808
2	369	10	560	18	851
3	389	11	590	19	897
4	410	12	622	20	946
5	432	13	655	21	997
6	455	14	690	22	1051
7	480	15	728	23	1108
8	506	16	767	24	1167
				25	1217

Figure 4.3. Impedance of LPZZ-4 measured with respect to 300 ohms.

5. LOG-SPIRAL ANTENNAS

5.1 Purpose

The purpose of this investigation is to study characteristics of present

forms and new versions of the conical logarithmic spiral antenna

5.2 Factual Data

5.2.1 Research Staff - J. D. Dyson and G. L. Duff

5.2.2 Status

As outlined in previous reports, a detailed study of the near fields on

the conical antenna is being made to determine the location and width of the

principal radiation region. Approximate models to the antenna have been con- .

sidered and the far fields of these models have been calculated using data

measured in the near fields of the antenna.

The first model consists of an array of loops as shown in Figure 5.1a.

Each loop serves to approximate one turn of the log-spiral antenna. The data

measured in the near fields of each turn are assigned to each loop in the

calculation. The second model consists of the array of uniform helical cells

shown in Figure 5.1b. Each helical cell serves to approximate one turn of the

spiral antenna (see Figure 5.2) and measured near field data are used.

The far fields of a uniform helical cell, that is one turn of a uniform

helix, were calculated by the vector potential method. The current assumed

was of the form $\bar{I}e^{-\zeta\phi}$, a constant amplitude traveling wave. Such calculations

have been made previously for the case where ζ is an integer. These calculations

were modified for an arbitrary real ζ and the results are expressed in terms of

a finite number of Anger's Functions, rather than the usual infinite sum of

Bessels functions of the first kind. The fields due to each cell were summed

giving a resultant field. The calculations were done on the University of

Illinois IBM 7090 computer.

The far field patterns were first calculated for a total of 25 arrayed

helical cells, which represented one particular log-spiral antenna. Subsequently

the computer was programmed to calculate the far fields, excluding one cell each

time from the small end of the antenna, i.e., patterns were calculated first for

a total of 25 cells, then 24, 23, and so on. By this method it was expected

24

LOOP CELL
MODEL

HELICAL CELL
MODEL

CONICAL
LOG SPIRAL

NOTE: THE METHOD
OF "FEEDING" THE
TWO MODELS IS
SHOWN BY THE
INDICATED PHASE.

MEASURED
PHASE
ALONG
ANTENNA

a.

b.

c.

Figure 5.1. Models used to calculate radiation patterns.

ONE CONICAL LOG
SPIRAL CELL

CORRESPONDING
HELICAL CELL

APPROXIMATION CONSISTS
OF A UNIFORM HELICAL
CELL ON A CYLINDER WITH
DIMENSIONS AS SHOWN.

$2a$

$\frac{h_c}{2}$

$2a$

h_c
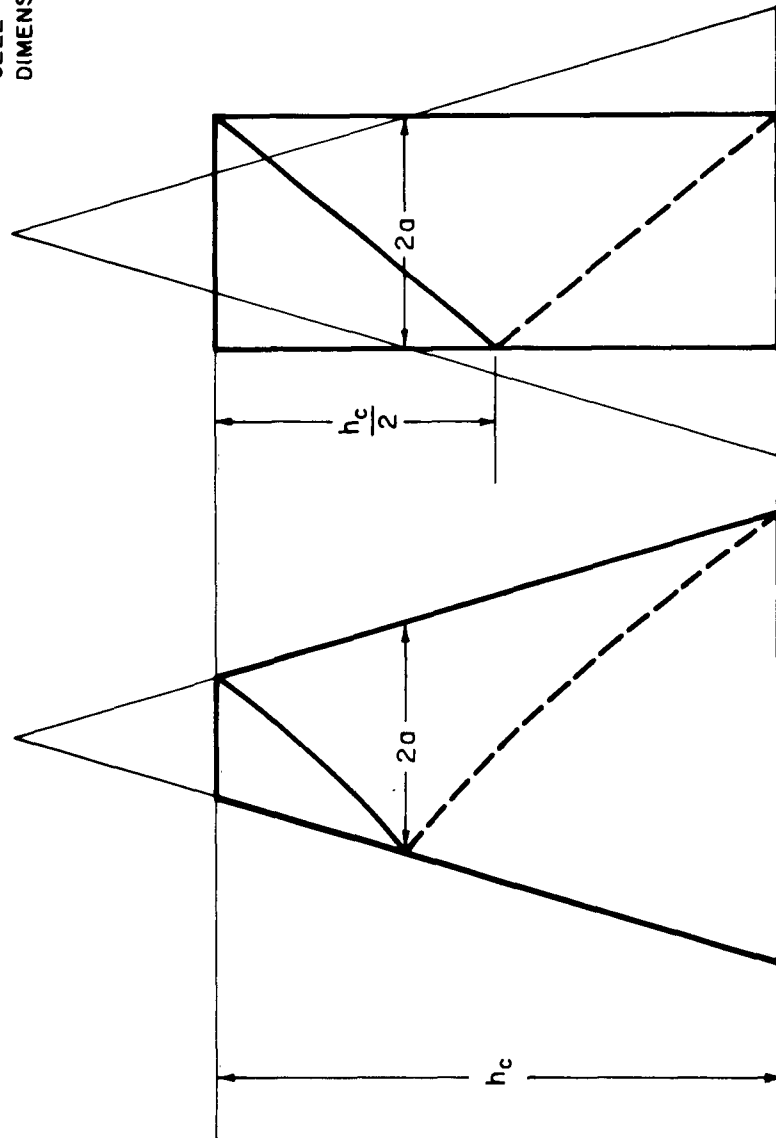
Figure 5.2

that the far field patterns would change as soon as cells were removed from
the radiation region. The amount and nature of this change would therefore
give an indication of the relative importance of each cell as a radiator.

The results calculated using the loop model and the helical model were
essentially the same. The beamwidths of the radiation patterns for the array
of helical cells were consistently 5 to 10 degrees greater than those of the
loop model. For the time being it was decided to continue only with the helical
model since it should be a better physical approximation to the log-spiral
antenna.

The patterns calculated to date have larger beamwidths than the measured
patterns, and the difference between the beamwidths of the two principle cuts
is larger than has been measured. These patterns were calculated using data
measured at a distance of 10 mm ($\lambda/50$). Near field data are presently being
measured at a distance of 2 mm ($\lambda/250$) from the antenna and the patterns
calculated with this new data may coincide better with the measured patterns.

The initial calculations have shown that the turns on the antenna immediately
preceeding the region of rapid decay of the near fields contribute significantly
to the far fields and, hence must be included as part of the radiation or "active
region". This conclusion is also indicated by measurements presently being made
at 2 mm from the antenna, although patterns have not yet been calculated.

This result is anticipated if one considers that the fields become more
loosely bound to the structure as the wave progresses from the feed point to
the marked decay region.

A typical radiation pattern for a tapered array of loops is shown in
Figure 5.3. The pattern indicates that such a structure could well be a
successful logarithmic periodic antenna with characteristics quite similar to
those of the log-spiral, but with possible greater ease of construction.

5.3   Plans for the Next Interval

Further calculations will be made using the data measured at 2 mm from
the log spiral.

$$\frac{E\phi}{E_\theta}\bigg|_{\theta=0°} = 1.17$$

E_θ

E_ϕ
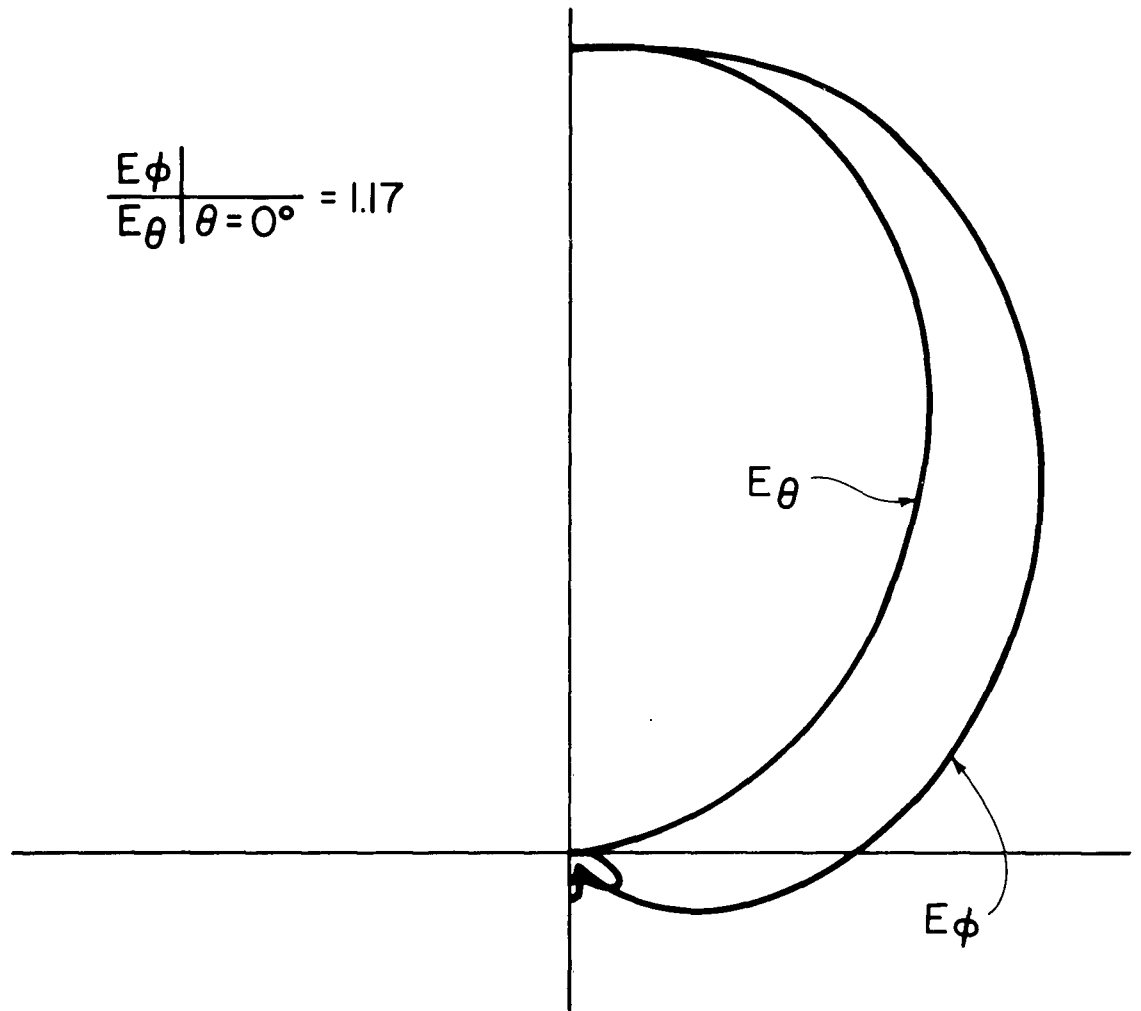
Figure 5.3. Typical radiation pattern for array of tapered loops.

6. AN INTEGRATED ANTENNA AMPLIFIER

6.1 Purpose

This investigation will concern the feasibility of utilizing varactor diodes in a backfire antenna to produce amplification in the antenna itself and thereby improve signal-to-noise performance.

6.2 Factual Data

6.2.1 Research Staff - P. G. Ingerson, P. E. Mayes

6.2.2 Status

The approximation that in the transmission line region of the log-periodic dipole antenna the dipoles produced a constant loading per unit length was checked. It was found that the phase velocity does have a constant slowing over a range of 8 cells which are located directly in front of the active region. (The number of cells for which this is true is determined by τ). These 8 cells will be the main amplifiying region.

The integrated slab and parallel plate line which will propagate the pump and signal waves was checked. While in theory there should be little coupling between them, measurements showed decoupling to be on the order of 10 to 15 db. At present this coupling is believed to be due to lack of symmetry in the antenna feed system.

6.3 Plans for the Next Interval

Measurements are being made to determine if it will be possible to use self-biasing of the diodes as planned. If the effect of the unbiased diodes in the line cannot be overcome, then dc biasing will have to be used.

7. WAVE PROPAGATION ON HELICES

7.1 Purpose

To understand the behavior of the tape helix it is sometime useful to study the sheath helix which is a mathematical model with an anisotropic cylindrical current sheet.

The determinantal equation for the sheath helix has been derived by others and the real Brillouin (k-β) diagram found. From the k-β diagram people have explained, more or less satisfactorily, many properties of the helix when used as a waveguide in a traveling wave tube or as an antenna.

7.2 Factual Data

7.2.1 Research Staff - P. Klock, R. Mittra

7.2.2 Status

The k-β diagram for the bifilar tape helix was obtained for various tape widths for pitch angles of 10° and 17°. Some sample results are shown in Figures 7.1a, 7.1b, 7.2a, 7.2b, 7.3a and 7.3b.

The results for modes 1 + 2 are similar to the results for modes 1 + 2 for the monofilar tape helix. The major differences are as follows:

1) The deviation of the real part of the phase constant from the line corresponding to the velocity of light is more for the bifilar helix than the deviation which occurs in the case of the monofilar helix.

2) The maximum value of the imaginary part of the phase constant is greater for the bifilar helix than it is for the monofilar helix.

Also during the past period a study of the k-β diagram for low frequencies was made. A graph showing typical results is shown in Figure 7.4. The helix has been used by others to produce a slow wave. The first approximation used is that the velocity along the axis is $v_z = c \sin \psi$. However, by inspecting Figure 7.4 one predicts that the wave will have a greater velocity in the z direction than that given by $c \sin \psi$. The deviation from the $c \sin \psi$ line close-up is substantial for very thin tapes and is greater for thicker tapes. This result is the opposite that one desires if the purpose of using the helix is to obtain a slow wave or to make the structure smaller.

7.3 Plans for the Next Interval

The current on a bifilar equiangular spiral will be calculated using

BIFILAR HELIX

$\psi = 10°$

$\alpha = .4$

$\alpha = .1$

$\alpha = .0001$

$\alpha = 10^{-30}$

$\beta_r = 1 + k$

$k = \beta_r \sin \psi$

$k = \beta_r \sin \psi$

$\beta_r = 1 - k$

k

β_r

Figure 7.1a

30

Figure 7.1b

BIFILAR HELIX

$\psi = 17°$

$\alpha = .4$

$\alpha = .1$

$\alpha = .0001$

$\alpha = 10^{-30}$

β_r

κ

0   .2   .4   .6   .8   1.0   1.2   1.4   1.6   1.8   2.0   2.2   2.4   2.6

0   .1   .2   .3   .4   .5   .6   .7   .8

Figure 7.2a

Figure 7.2b

BIFILAR HELIX
$\psi = 17°$

Figure 7.3a

BIFILAR HELIX
$\psi = 17°$

β_i

η

k
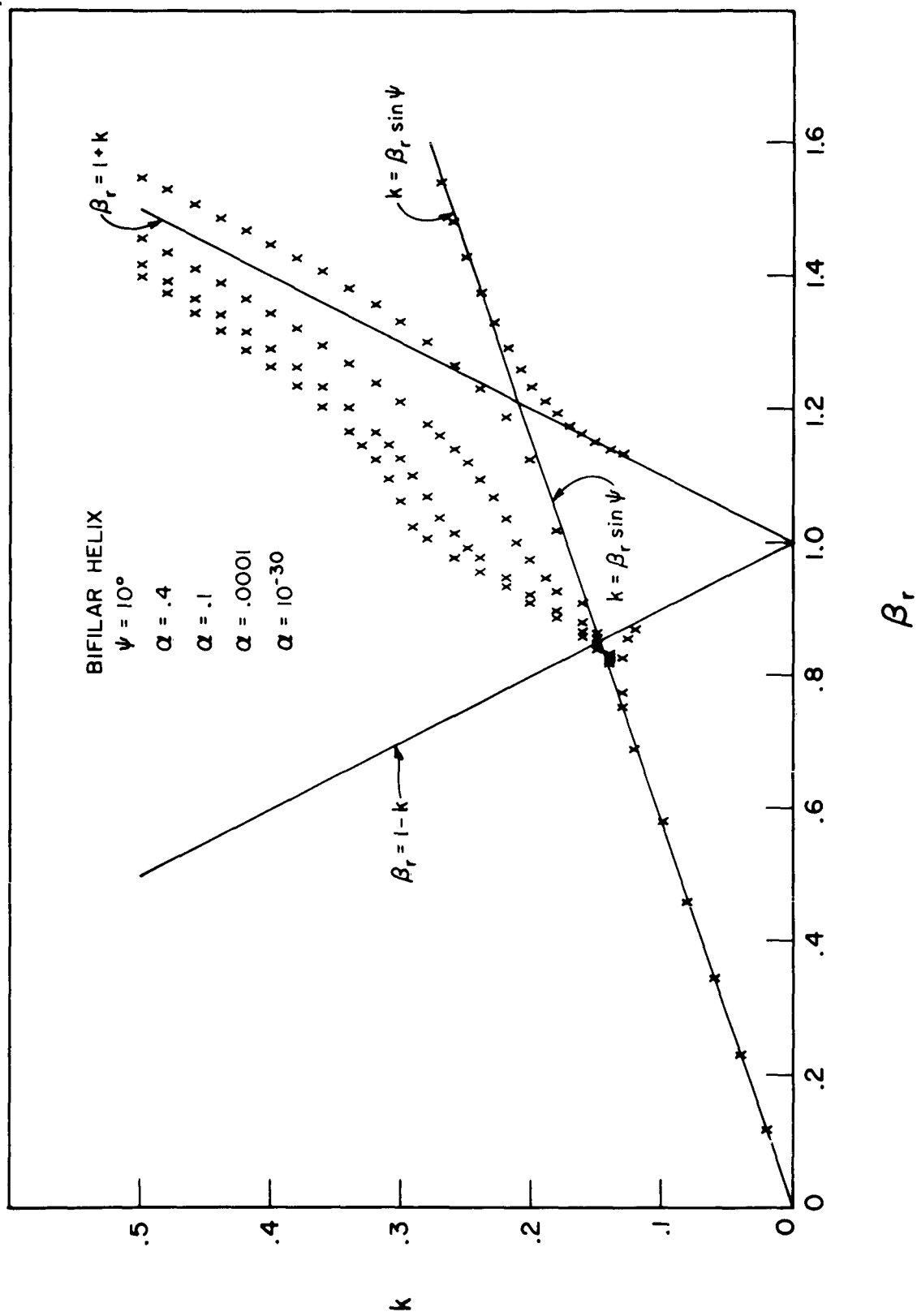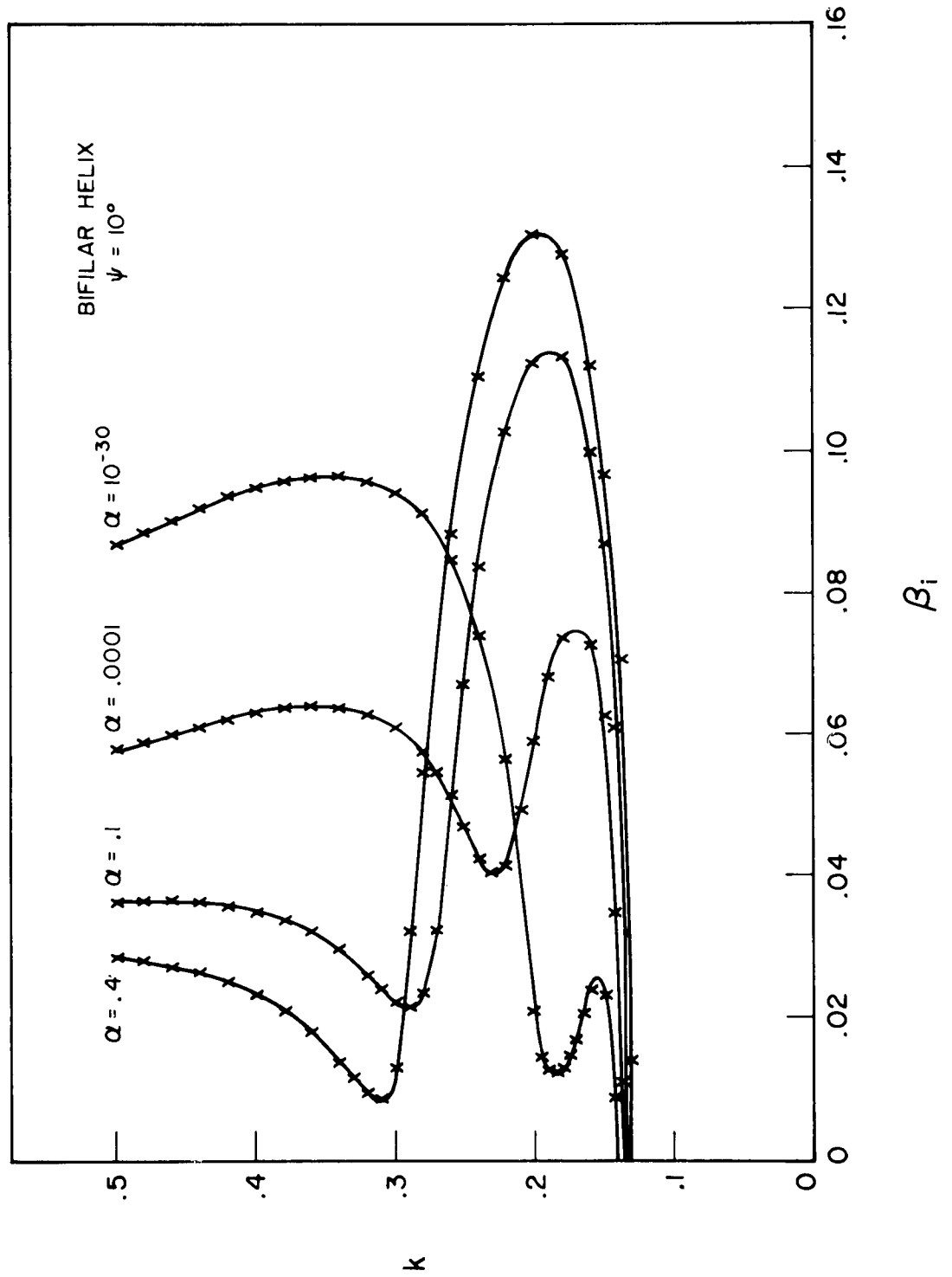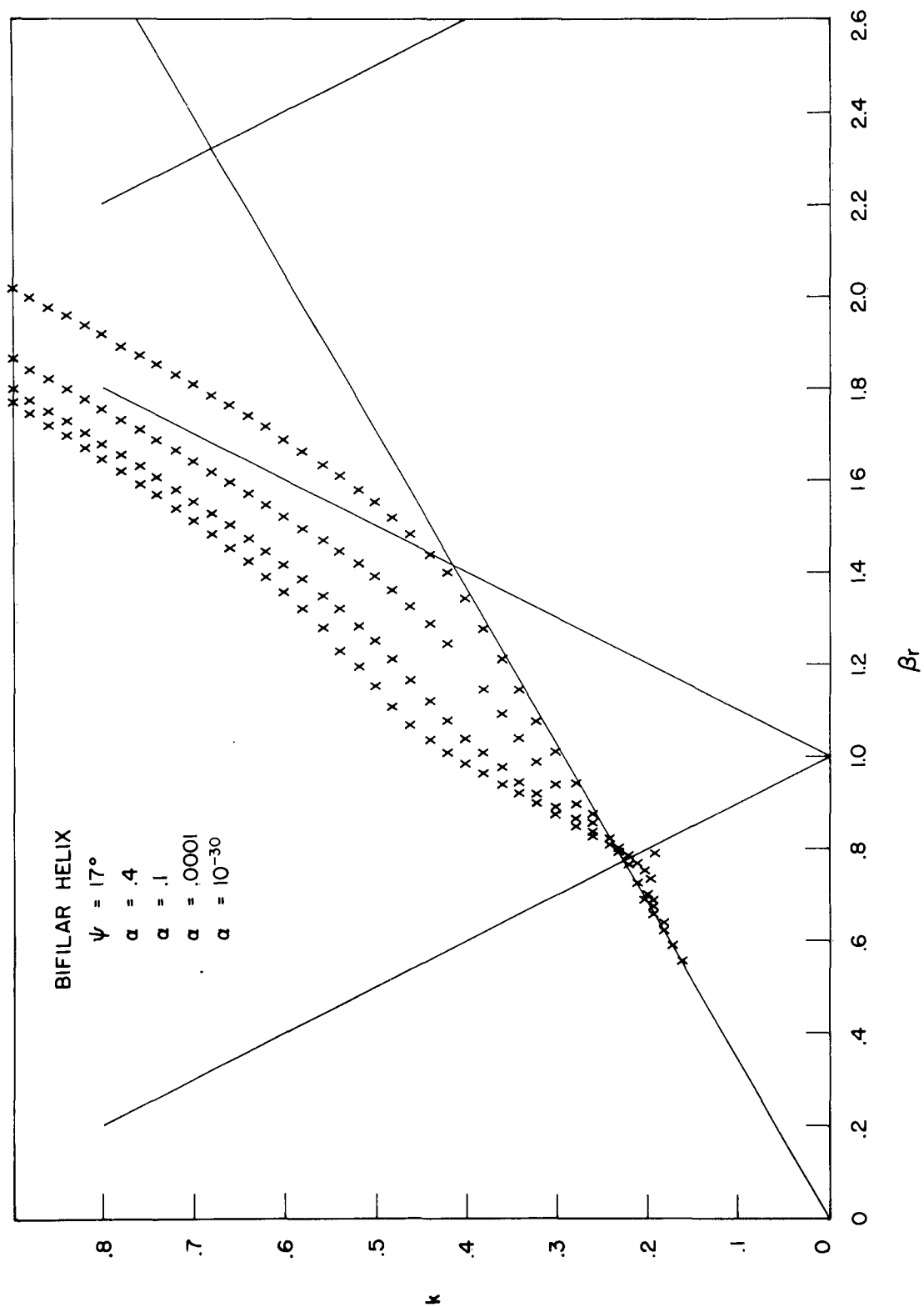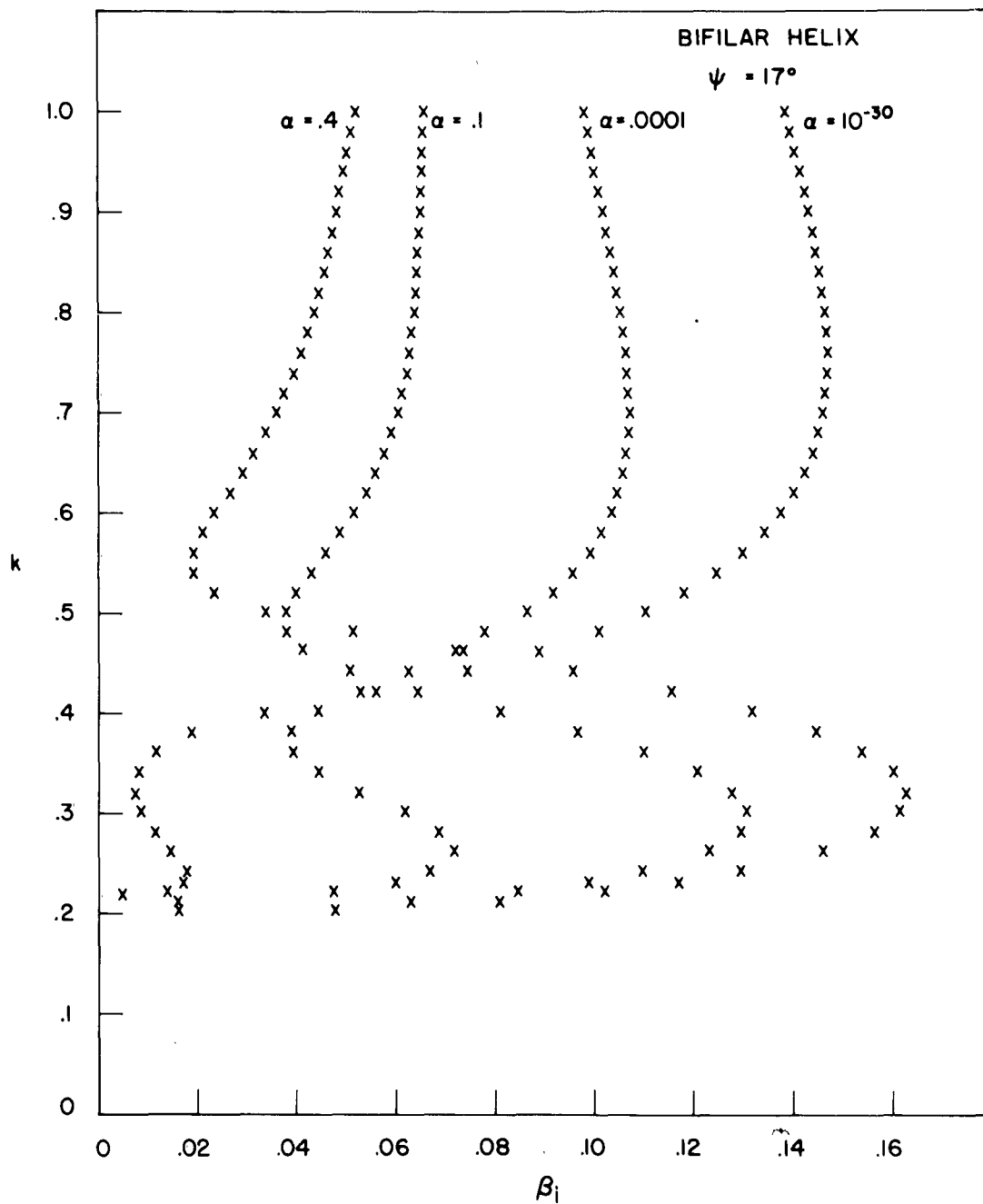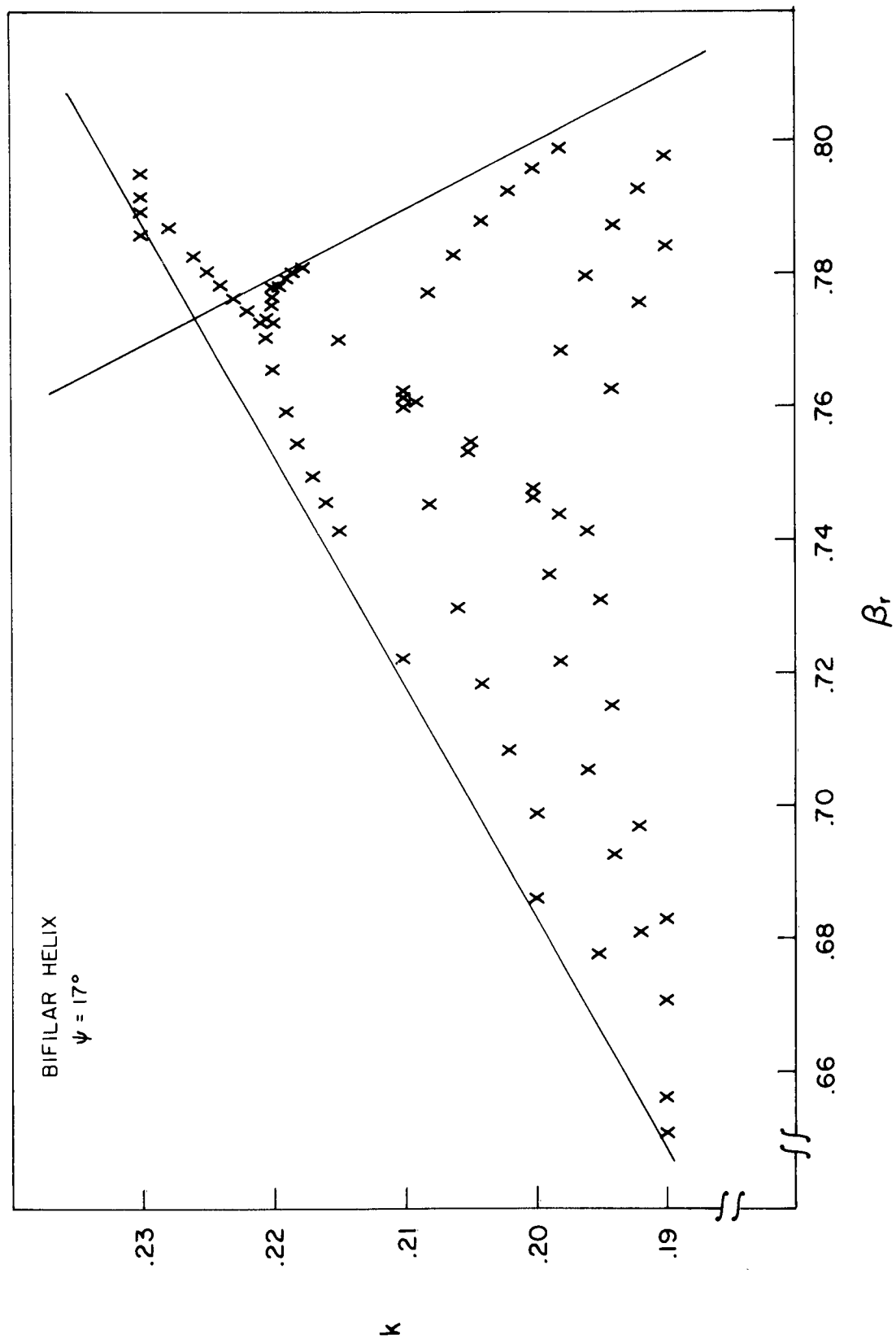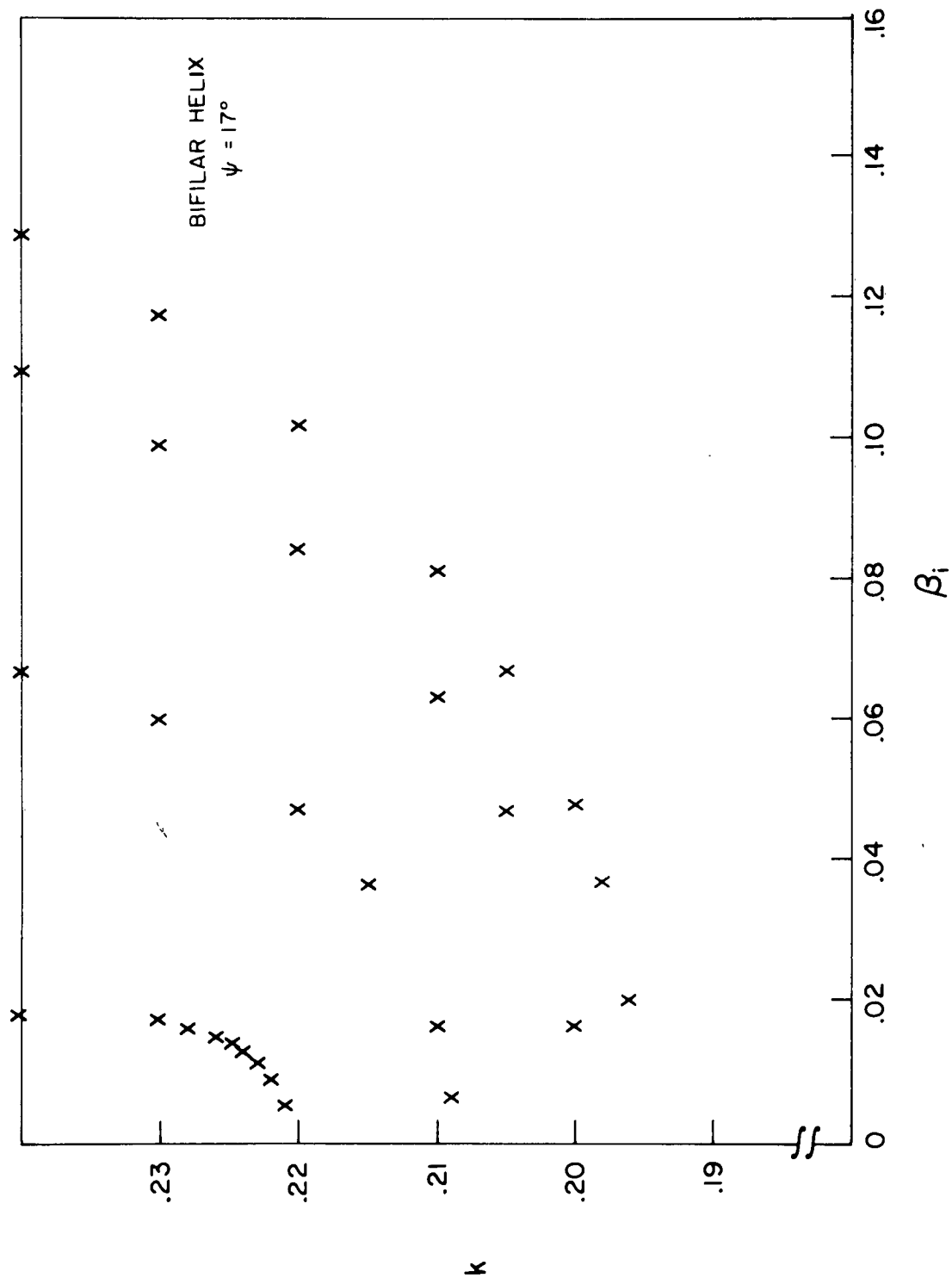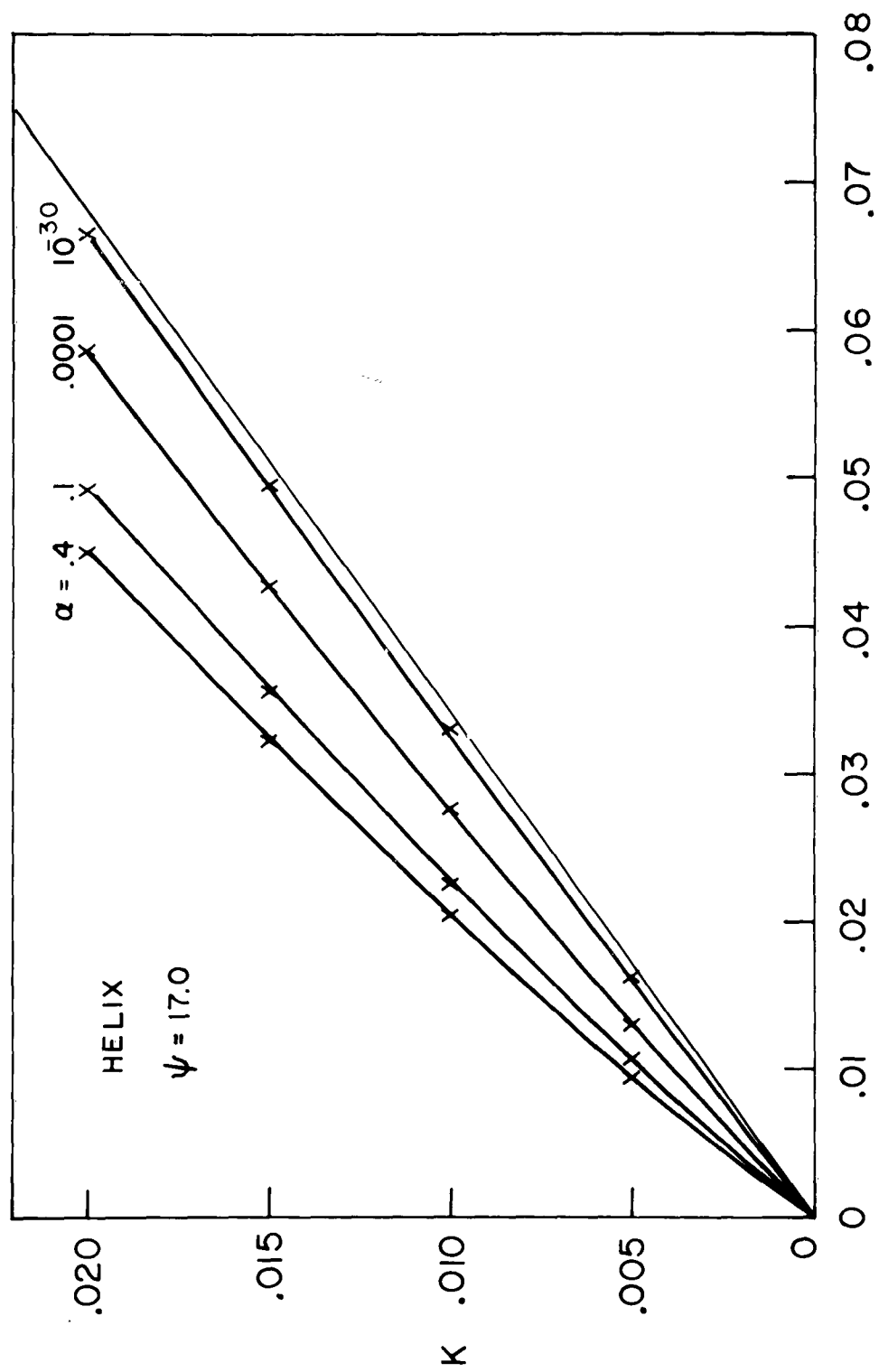
Figure 7.3b

Figure 7.4

the results for mode 1 of the k-β diagram for the uniform helix and the WKB
method of approximating the solution to the differential equation with
variable coefficients.

8. INVESTIGATION OF A CLASS OF PERIODIC STRUCTURES

8.1 Purpose

The purpose of this project is to study a class of periodic structures for wideband applications.

8.2 Factual Data

8.2.1 Research Staff - S. Laxpati, M. Wahl, R. Mittra

8.2.2 Status

We shall continue to report in the format used in the last quarterly report and divide up the report in this section into four subsections as follows:

(a) Investigation of Uniform and Tapered Surfaces

A paper entitled, "The Letter-Rack Antenna - A Wideband Flush-Mounted Antenna of Log-Periodic Design" was presented at the IEEE Convention.

Impedance measurements have been made on the Letter-Rack Antenna and are shown in Figure 8.1. Preparation of the manuscript for a technical report describing the Letter-Rack Antenna has been completed and the report will be issued shortly.

Future work: No further work on this particular antenna is planned in the near future.

(b) Waveguide with Glide-Reflection Symmetry

The determinantal equation for propagation constant β_o in the waveguide with glide reflection symmetry has been reported in the last quarterly report.[1]

This equation studied now includes the terms of the type $e^{-\alpha_n y}$, $n = \pm 1$, [α_n being the transverse propagation constant] and has been solved numerically on IBM 7090 digital computer. Numerical solution for β_o is obtained as a function of k, the free space propagation constant, with the separation between the plates "t" as a parameter.

Figure 8.2 shows the plot of k against β_o (Real Solution) for three values of t. This plot once again demonstrates the effective period of this waveguide structure as d/2, and not d, the latter being the translational period. However when t is very large the structure behaves as though it had a period d.

Figure 8.3 shows the plot of k against β_o for t = .06, including real and approximate complex solutions for two different modes. Note that the complex solution for β_o does not exhibit the familiar filter type cutoff at (Re β_o)(d/2) = π, and that it deviates considerably from this line.

A complete study of these results is being made currently. It is hoped that this study will help explain some aspects of the behavior of several periodic and log-periodic structures. A technical report on this study is also planned for the near future.

Figure 8.1. Input impedance of Letter-Rack antenna referred to 50 ohms

Figure 8.2

40

Figure 8.3

41

#	f Mc
1	960
2	900
3	850
4	800
5	750
6	700
7	650
8	600
9	550
10	500
11	450
12	400
13	350
14	300
15	250
16	200
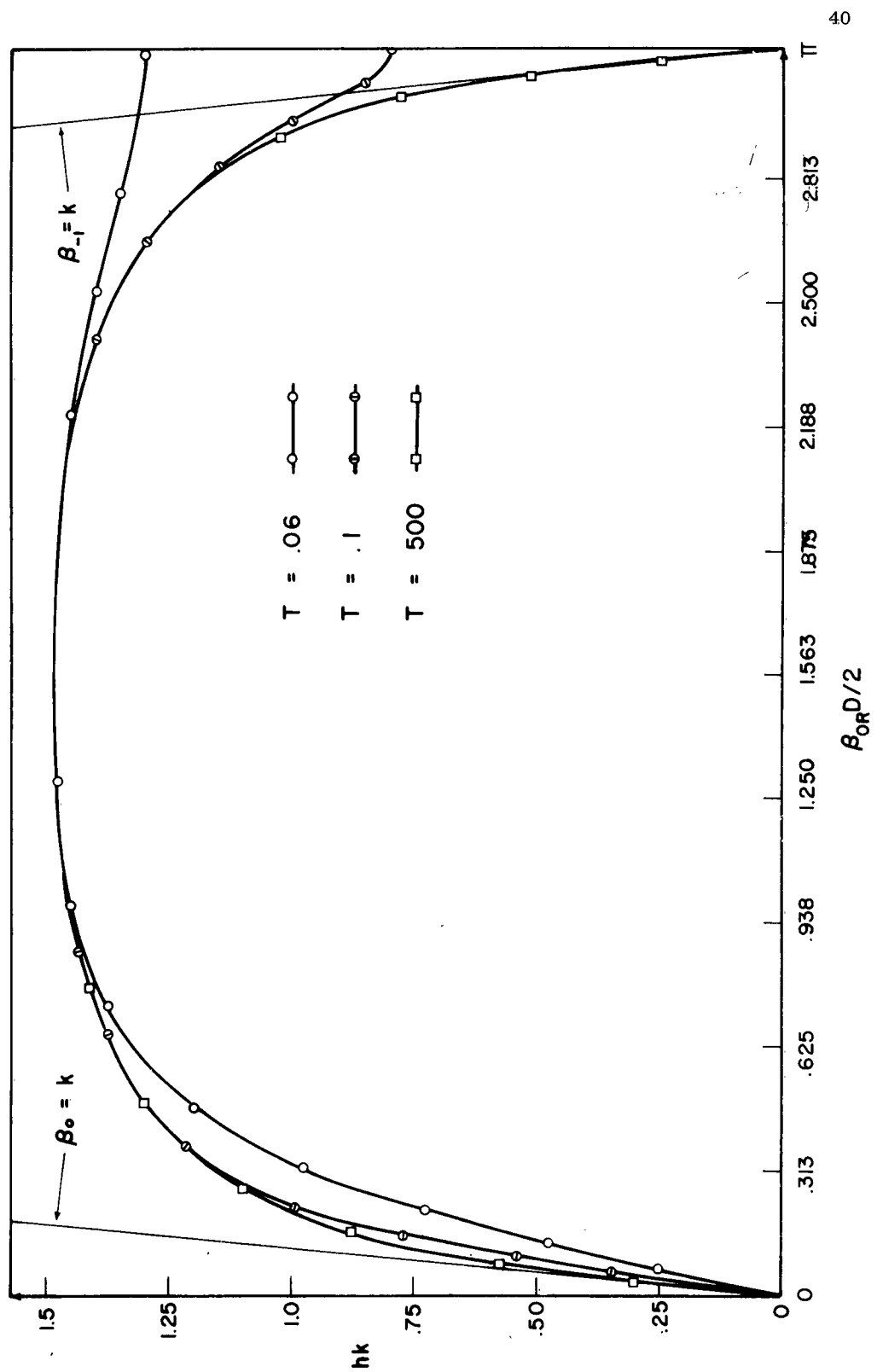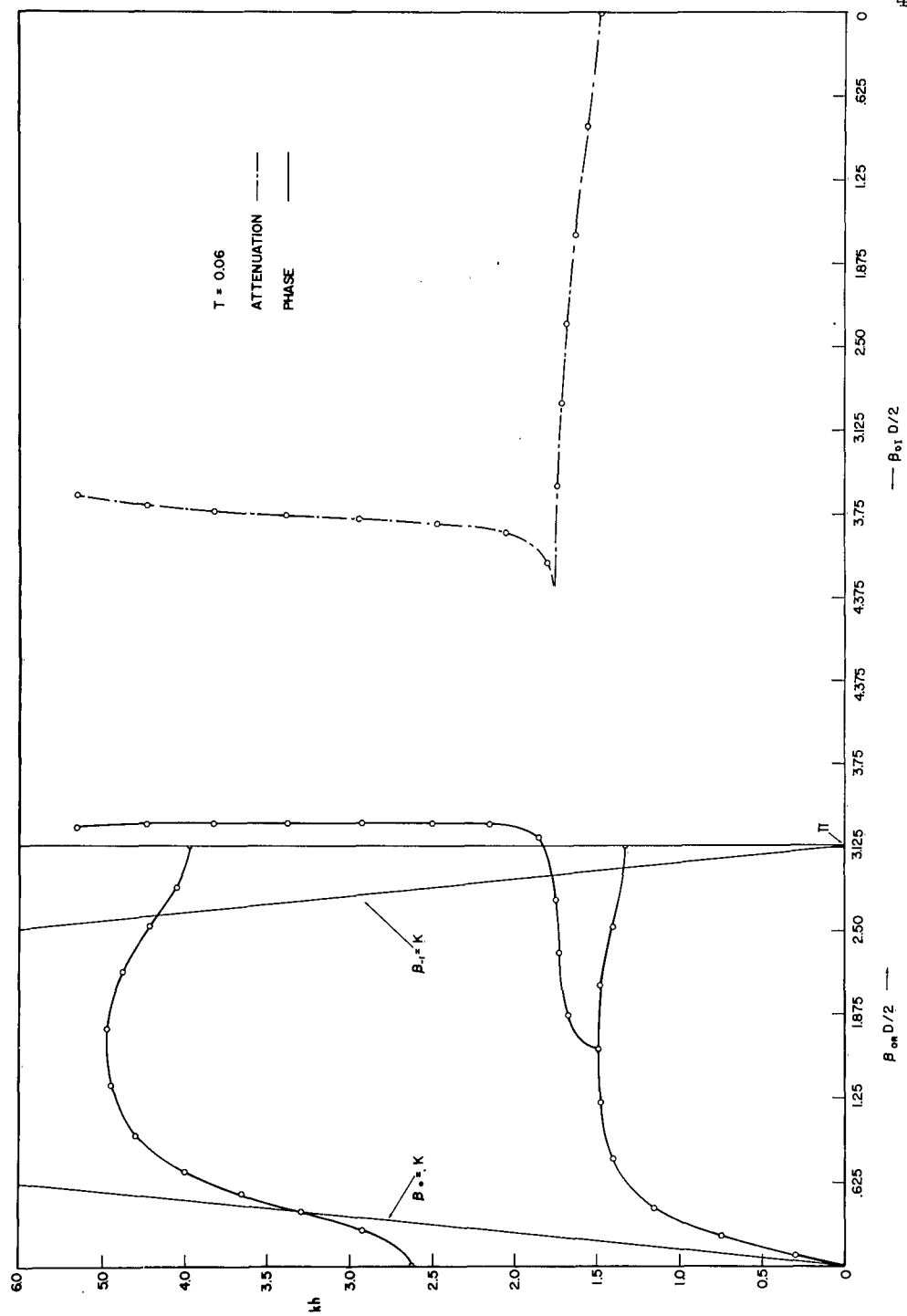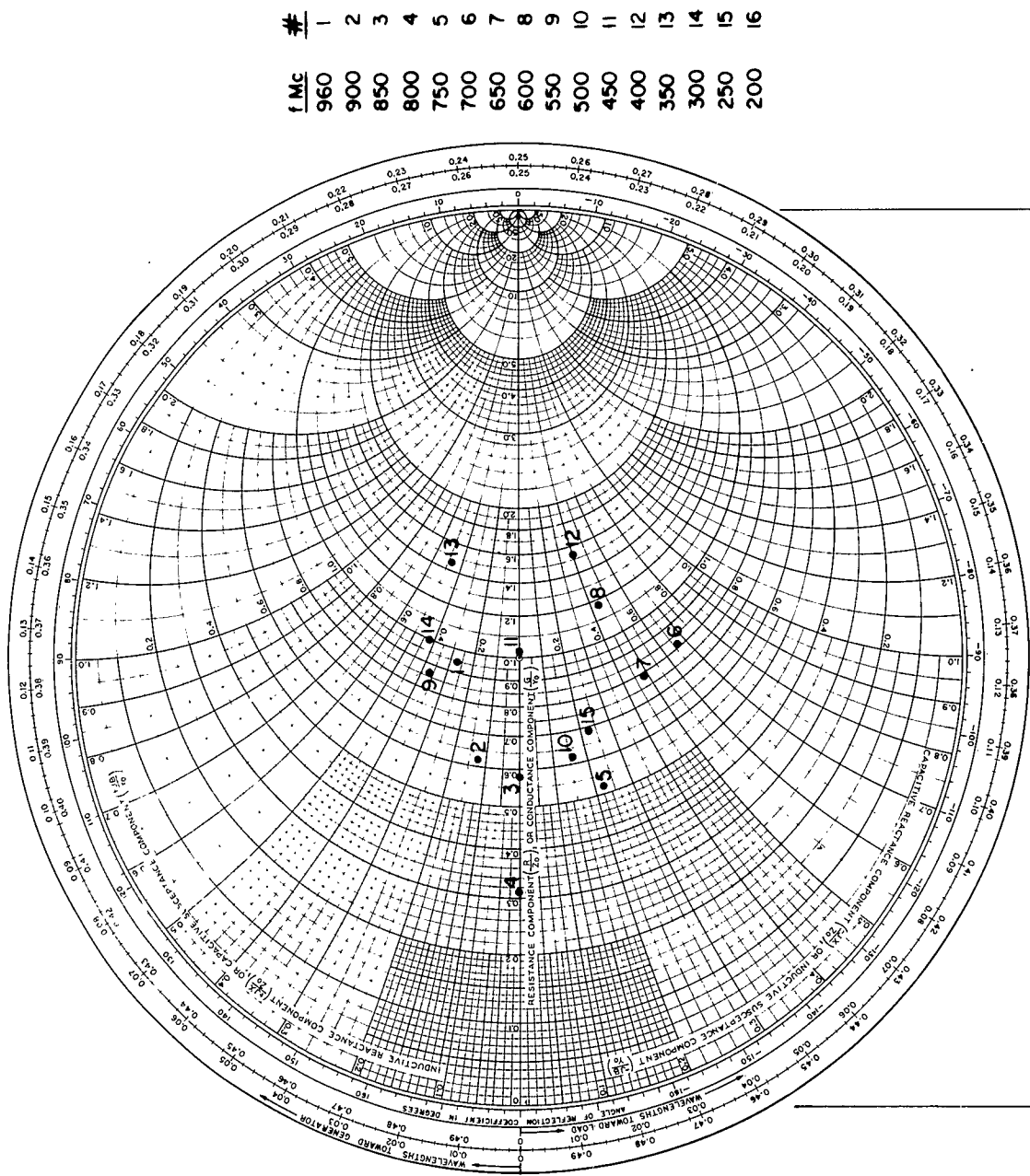
Figure 8.4. Input impedance of LP folded dipole array referred to 300 ohms

(c) Log-Periodic Folded Dipole Array

The Log-Periodic Folded Dipole Array, the principle of design of which is the same as used for constructing the feed system of the Letter-Rack Antenna, has been studied further. Main effort was devoted toward measuring the impedance of the antenna, since the patterns which were measured during the last quarter looked quite encouraging. An impedance model was built for the frequency range 250-900 MCS. The impedance plots are shown in Figure 8.4. The impedance measurements were obtained on the open 300 Ω Lecher wire line.

Future work: It is planned to build several variants of this basic structure, as for example the V-array.

(d) Log-Periodic Delta Array
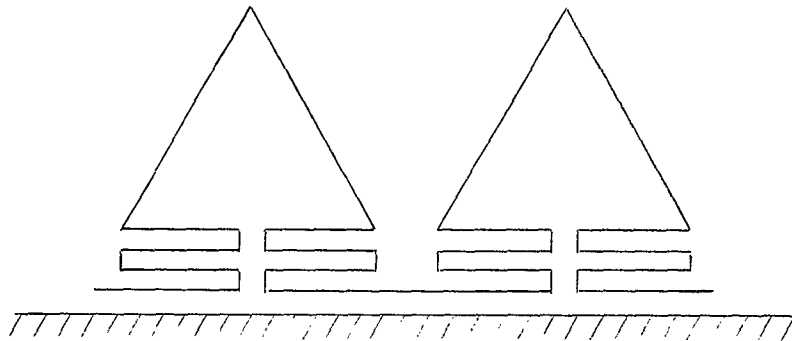
Figure 8.5

Some variants of the Delta array, one form of which was reported in the last quarterly report, are presently being considered. One such configuration is shown in Figure 8.5.

8.3 Plans for the Next Interval

A study of different versions of the $\triangle$ - array will be continued.

9. TRANSMISSION BETWEEN ANTENNAS WHEN THE FAR FIELD APPROXIMATION DOES NOT APPLY

9.1 Purpose

The purpose of this research is to determine the transmission coefficient between antennas located in their near fields.

9.2 Factual Data

9.2.1 Research Staff - J. R. Pace, G. A. Deschamps

9.2.2 Status

Work on the section has been discontinued.

10. RADIATING LENS ILLUMINATED FROM A GOUBAU BEAM-WAVEGUIDE

10.1 Purpose

The purpose of this project is to determine the feasibility of developing a high resolution millimeter antenna by coupling from a Goubau beam-waveguide to a radiating lens.

10.2 Factual Data

10.2.1 Research Staff - P. E. Mast, J. F. Kauffman

10.2.2 Status

During this reporting period the Goubau beam-waveguide experimental setup was moved into a new Emerson-Cummings Anechoic Chamber, and the transmitting and receiving systems were optimized. This new facility allows for greatly refined measurements at millimeter wavelengths.

A number of mechanical refinements of the beam-waveguide have been completed. Pointers and dials have been added to the lens holders, and the reflector-type line shield has been replaced by an absorbing shield. These changes have improved the pattern symmetry, and have made it much easier to make pattern measurements. An absorbing ring placed on the aperture lens holder gives a decrease of several db in the first side lobe.

To check whether or not the fundamental mode had been established on the beam-waveguide, patterns were taken with beam-waveguides of 5, 6, 7, and 8 interactions. It was found that these changes in the number of iteractions produced no noticeable change in the radiation patterns.

Theoretical work has been done on the computation of the side lobe level of a truncated Gaussian aperture distribution, and on a more accurate lens design using a Fresnel approximation.

10.3 Plans for the Next Interval

Work will be continued on the calculation of the theoretical side lobe level and on the Fresnel approximation lens design. The design and construction of a lens to focus the antenna beam at a point in the near field will be undertaken.

11. ZONE PHASE PLATES

11.1 Purpose

The purpose of this study is to investigate the operation of zone phase plates.

11.2 Factual Data

11.2.1 Research Staff - H. A. Shubert

11.2.2 Status

The general problem of the scattering of a plane E.M. wave by an infinite periodic grating of parallel dielectric bars is best formulated as an infinite set of equations. The unknowns in these equations are the complex amplitudes of the space harmonics which appear because of the periodicity of the structure. The equations are not generally directly solvable, so some iteration procedure must be used. The method of iteration being used in the present case is one which has proven very effective in other problems. It is a matrix iteration method. The equations for the space harmonic amplitudes may be written in matrix form as:

$$MA = F \tag{11.1}$$

where A is a column matrix of the unknown complex amplitudes; M, the coefficient matrix, is a function of the physical parameters, and is a square matrix; and F is a column matrix derived from the incident wave.

If the inverse of M were known, the problem would be solved. Since it is not, an iteration procedure is necessary.

The matrix M is separated into two parts

$$M = M_o + M_1 \tag{11.2}$$

with the characteristics that the inverse of M_o is known, and the matrix M_1 is in some sense small compared to M_o. It will be possible to write

$$M^{-1} = \left[M_o (1 + M_o^{-1} M_1) \right]^{-1} = \left[1 + M_o^{-1} M_1 \right]^{-1} M_o^{-1} \tag{11.3}$$

Then if the product $M_o^{-1} M_1$ is small compared to the unit matrix, (in some sense), so that the first term on the right hand side may be expanded in a convergent series of matrices.

$$\left[1 + M_o^{-1} M_1\right]^{-1} = \left[1\right] - \left[M_o^{-1} M_1\right] + \left[M_o^{-1} M_1\right]^2 - \ldots \tag{11.4}$$

In the method chosen for decomposition the M_o matrix is taken to be of the double alternate form, which has a known inverse. By using this form it has been shown possible, in other problems, to sum directly some of the terms of the matrix in Equation (11.4), and show that they were the dominant contributions.

Unfortunately, this method of decomposition of the matrix, if used directly, leads to an indeterminant form for M_o. That is, M_o has two sets of two identical rows.

A modification for the decomposition has been found which resolves the indeterminancy, and still retains the desired simple form. No further work has been finished on this formulation, but numerical calculations are in progress to determine whether it is indeed feasible.

11.3 Plans for the Next Interval

Work will continue on this project, both theoretical and experimental.

12. STUDY OF A CLASS OF GRATING PROBLEMS

12.1 Purpose

The purpose of this investigation is to study the diffraction properties of a class of uniform and modulated grating type structures. The Brillouin diagrams for these structures will be computed, and the scattering properties of the gratings in both the near and far field regions will be investigated.

12.2 Factual Data

12.2.1 Research Staff - J. R. Pace, R. Mittra

12.2.2 Status

A paper entitled, "A New Technique for Solving a Class of Boundary Value Problems", was presented at the 1963 Spring URSI meeting in May. This advanced a technique for obtaining a formally exact solution for a broad class of problems, of which the grating problems previously discussed[2] are a part.

The field solution which is valid both for near and far field calculations is obtained in terms of a matrix representation, the matrix being of infinite order. The matrix elements are expressible in terms of the "scattering coefficients" of an auxiliary problem. This auxiliary problem is one which can be solved exactly by the Weiner-Hopf, function-theoretic, or other rigorous methods. While it is true that the present solution is expressed in terms of an infinite series, it is likely that the dominant terms in the series can be separated from the whole. This method has been applied to certain waveguide discontinutity problems and some numerical calculations have been made. Some of these will be presented in this section.

A detailed description of this technique will be made in a forthcoming technical report, presently in preparation. It is hoped that this report will be released this summer. The central idea behind this method is not difficult to grasp, but it is novel, and it should be presented with a proper explanation.

As a preliminary to studying the grating problems, a detailed study of some waveguide discontinuity problems will be made. These problems are quite interesting for their own sake. However, by handling the waveguide discontinutiy problems, further insight into the general technique will be gained. This insight will be useful in handling the grating problems.

To illustrate that the dominant terms in the series representation can be identified and easily computed, consider the inhomogeneous bifurcated waveguide. Marcuvitz[3] has considered the homogeneous bifurcated guide. Cronson[4] has solved approximately the inhomogeneous bifurcated guide by solving a truncated set of algebraic equations.
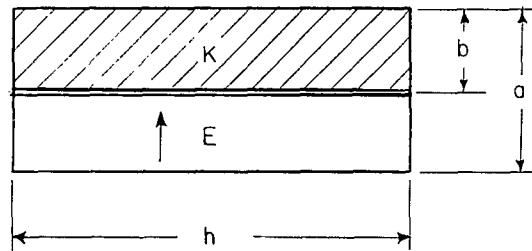
Figure 12.1. Inhomogeneous bifurcated waveguide

Instead of solving the boundary value problem above in the rectangular geometry, it is easier to solve the parallel plate waveguide problem.
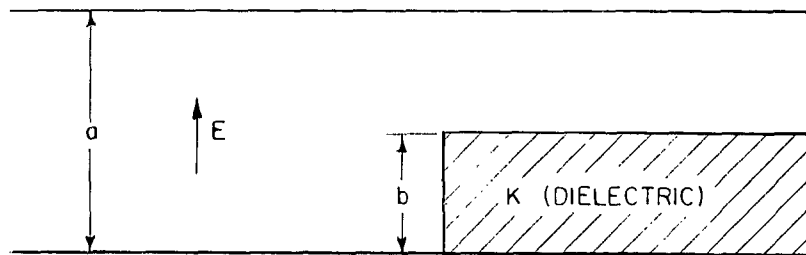
Figure 12.2. Equivalent parallel plate waveguide problem

The reflection coefficient for the dominant mode in the rectangular guide can be computed simply from the expression for the reflection coefficient of the TEM mode in the parallel plate guide by replacing k_o^2 by $k_o^2 - (\frac{\pi}{h})^2$. See, for instance, Marcuvitz[3].

Computations were made for the case where b = a/2. For this case

$$\Gamma_{input} \sim \frac{1}{2} \quad \frac{\Gamma^{(o)}}{1 - \Gamma^{(o)} S_{11}}$$

where

$$S_{11} = \frac{1}{2} \Bigg/ \left[- 4\, \epsilon\, \ln 2 + 4 \sum_{n=1}^{\infty} \left\{ \tan^{-1} \frac{1}{\left\{(n/\epsilon)^2 - 1\right\}^{1/2}} - \frac{1}{n/\epsilon} \right\} \right.$$

$$\left. - 2 \sum_{n=1}^{\infty} \left\{ \tan^{-1} \frac{1}{\left\{(n/2\epsilon)^2 - 1\right\}^{1/2}} - \frac{1}{n/2\epsilon} \right\} \right] \quad, \quad 0 \le \lambda \le a/2$$

and $\quad \epsilon = \dfrac{k_o a}{2\pi} = \dfrac{a}{\lambda}$; $\qquad \Gamma^{(o)} = \dfrac{1 - \sqrt{K}}{1 + \sqrt{K}}$,

K = dielectric constant.

The above expression represents the first terms in the series for Γ_{input}. Note that in the limiting case

$$\lim_{K \to \infty} \Gamma^{(o)} \to -1$$

the dielectric looks far away like a metallic step.

Numerical comparisons were made with the results of other author's work. In particular, Williams[5] has calculated by means of the Weiner-Hopf technique

followed by a formulation in terms of an infinite set of equations, the reflection coefficient from a metallic step discontinuity in the parallel plate guides. Results are compared below.

Reflection Coefficient

$\epsilon = a/\lambda$	Author's Results	Williams' Results	
0.4	$-.408 \,\underline{/23.6}^{\circ}$	$-.438$	26°
0.7	$-.544 \,\underline{/2.1}^{\circ}$	$-.529$	No phase information
0.9	$-.523 \,\underline{/1.2}^{\circ}$	$.500$	

(Note that $\epsilon > .5$ means that more than the dominant mode is allowed to propagate).

12.3 Plans for the Next Interval

The technical report will be completed and issued. Further studies on a variety of problems will be made. The use of the University of Illinois IBM 7090 digital computer is contemplated.

13. FOCUSING OF RADIATION FROM A BUNCHED CERENKOV BEAM

13.1 Purpose

The purpose of this study is to investigate methods of coupling energy from a fast wave line source, such as Cerenkov radiators, into an antenna beam, a radiating aperture, or other device.

13.2 Factual Data

13.2.1 Research Staff - H. A. Shubert

13.2.2 Status

This project, which had been discontinued, is reopened for this report in order to publish the results of a theoretical calculation which has been made and which clarifies results obtained experimentally on the Archimedes Spiral Grating Cerenkov Coupler. The conclusion is drawn that the coupler performs very near to the optimum to be expected from its design. It produces a circularly polarized lobe normal to the coupler, which is nearly frequency independent over the frequency range of the waveguide feed.

In earlier reports,[5] the design of a Cerenkov beam coupler was discussed. The coupler took the form of an Archimedes spiral grating, milled from plastic, which acted as a phase correcting device. (See Figure 13.1) The grating was designed by physical optics considerations. The Cerenkov beam was treated as a fast wave line source, radiating conical wave fronts. The grating spacing was made such as to bend the incident conical wave normal to the grating, and the spiral arrangement shifted the phase so that contributions radiated from opposite sides of the grating added constructively on the axis. The result was presumably a circular polarized lobe normal to the grating.

Experimental results confirmed that a spiral grating does produce a circularly polarized lobe off the normal to the grating when fed by a fast wave line source normal to and at the center of the grating. The fast wave line source was simulated by an array of slots inclined at an angle of five degrees to the axis of a waveguide, and cut in the narrow wall. The slots' spacing was tapered so as to provide a constant radiation along the length of the array. As it happens, the equivalent velocity of the line source simulated by such an array of slots, has a variation with frequency of just the right sort, that the grating spacing 2Δ needed to focus its radiation is:

$$2\Delta = 2a$$

53

$$t = \frac{\lambda}{2(n-1)}$$

$$\Delta = \frac{\lambda}{2n\,\text{SIN}\,\theta_c}$$

DIELECTRIC

AIR

BEAM AXIS

Δ

DIELECTRIC

BUNCHED CERENKOV BEAM

BEAM AXIS

t

Δ
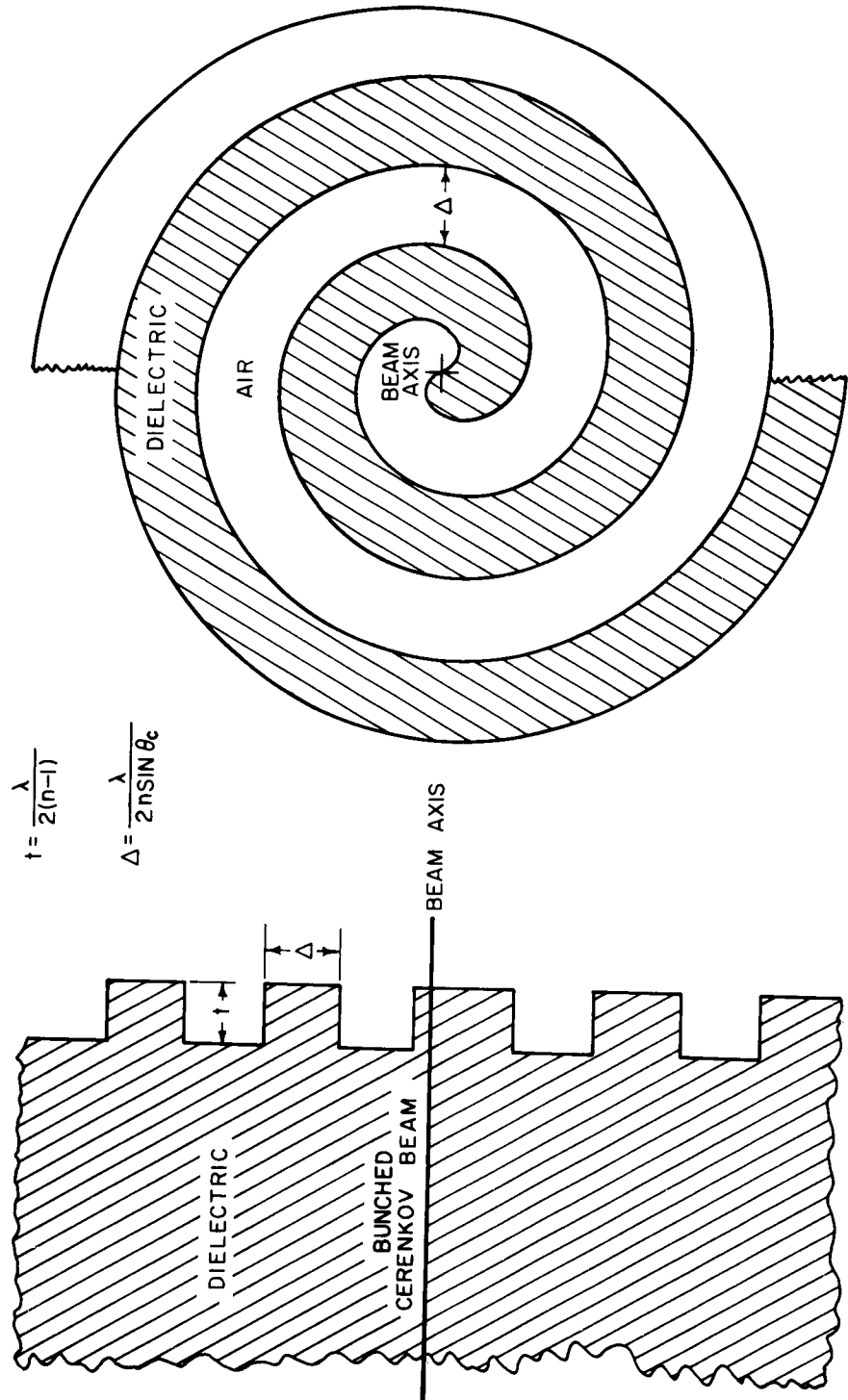
Figure 13.1. A Fresnel Zone Phase Plate for Focusing Cerenkov Radiation Into A Collimated Beam On Axis

where a is the width of the broad wall, independent of frequency.

Only the grating depth causes a frequency dependence. Indeed, the grating was found to produce a lobe on axis over at least a 1.5 to 1 frequency range (the limits of the test equipment). This lobe was almost frequency independent.

The experimental patterns also showed rather prominent side lobes, which were earlier ascribed to interaction between the source and grating producing nonuniform illumination of the grating. Since that time, however, a theoretical study of the pattern due to an optimum coupler has shown that probably only slightly better side lobe levels are possible without some more complicated control of the aperture illumination.

To study the theoretical optimum pattern, an aperture illumination of the form:

$$Ex \ (p^1\phi^1) = e^{i\phi^1} / \sqrt{p^{1}} \ \left\{ \cos \ \phi^1 \right\}$$

$$Er \ (p^1\phi^1) = e^{i\phi^1} / \sqrt{p^{1}} \ \left\{ -\cos \ \phi^1 \right\}$$

is assumed. This corresponds to two distinct phase transformations imposed on an incident conical wave, and to ignoring the component of the incident wave along the axis.

The phase shifts are: a linear transformation $\exp \left\{ jkp^1 \sin \theta_c \right\}$ where θ_c is the angle of propagation of the conical wave with respect to the axis, to focus the wave along the normal to the transformer; and a transformation linear with angle, $\exp \left\{ j\phi 1 \right\}$ to correct the polarization. The pattern function is then given by

$$Px(u) = \int_o^a \sqrt{p^{1}} \ dp^1 \ \int_o^{2\pi} d\phi^1 \ e^{j\phi^1} e^{jkp^1 \sin\theta} \cos \ (\phi-\phi^1)_{\cos \ \phi^1}$$

$$P_r(u) = \int_o^a \sqrt{p^{1}} \ dp^1 \ \int_o^{2\pi} d\phi^1 \ e^{j\phi^1} e^{jkp^1} \sin \ \theta \cos \ (\phi-\phi^1) \ \sin \ \phi^1$$

where θ and ϕ are the usual polar angles measured from and around the z axis, normal to the aperture.

The integration on ϕ^1 may be performed exactly to give

$$P_{x}(\theta,\phi) = \frac{2\pi}{k \sin \theta} \int_{o}^{k\ a\ \sin\ \theta} \sqrt{u}\ du \left\{ J_{o}(u) - e^{2j\phi} J_{2}(u) \right\}$$

$$P_{r}(\theta,\phi) = \frac{2\pi}{k \sin \theta} \int_{o}^{k\ a\ \sin\ \theta} \sqrt{u}\ du \left\{ iJ_{o}(u) + je^{j2\phi} J_{2}(u) \right\}$$

The term involving the zero order Bessel function, $J_{o}(u)$ may be seen to yield a circularly polarized lobe on axis ($\theta = 0$). The other term involving the second order Bessel function $J_{2}(u)$ gives a rather large side lobe whose state of polarization varies with angle ϕ around the axis. This lobe is situated at k a sin θ = the first zero of $J_{2}(u)$.

The results of a numerical integration of the above equations is shown in Figure 13.2a and 13.2b. For comparison, an experimental pattern of the actual grating is plotted on the same graphs. The similarity is obvious. The lack of nulls in the experimental pattern may be explained by the presence of a small cross polarized component in the incident wave due to the inclination of the slots.

The slight spread of the experimental pattern from the theoretical optimum may be due to the previously postulated interaction of the grating with the array of slots, or a slight variation of the velocity of the waveguide mode due to the slots.

It may be seen, however, that the experimental pattern is as close to the theoretical optimum as could reasonably be expected. It is therefore concluded that the design performed successfully.

13.3 Plans for the Next Interval

No more work is planned on this project.
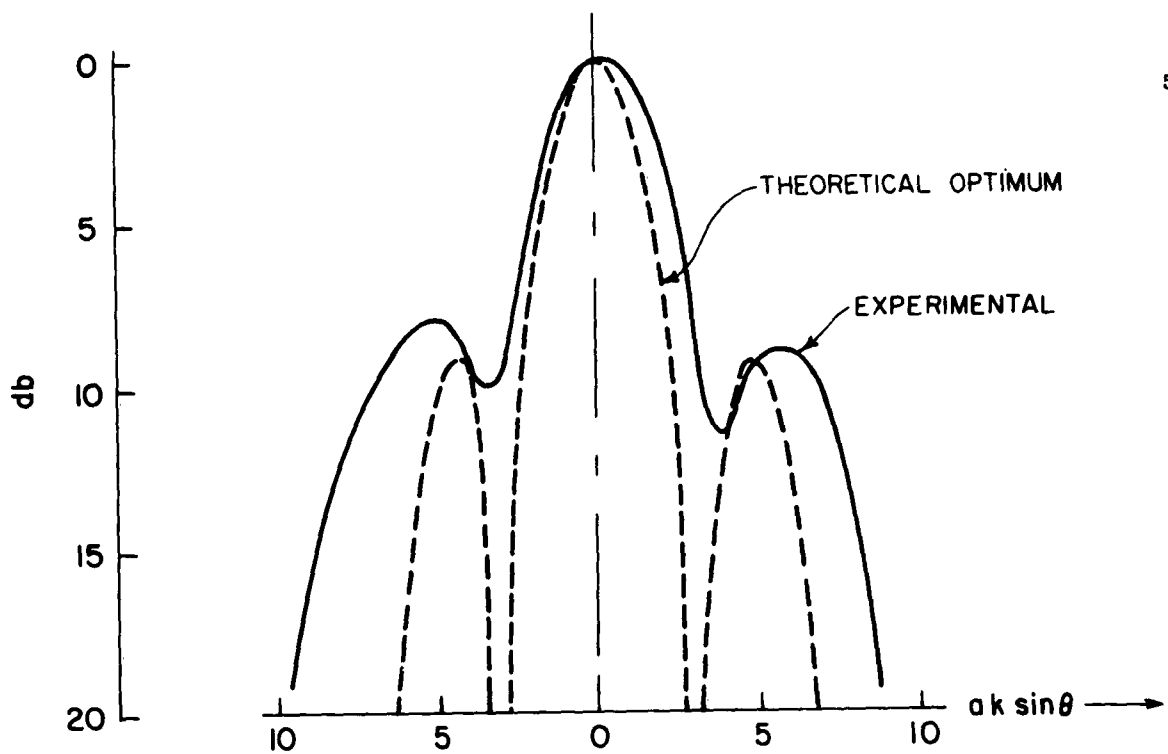
Figure 13.2a. Spiral Cerenkov Coupler - Horizontal Polarization
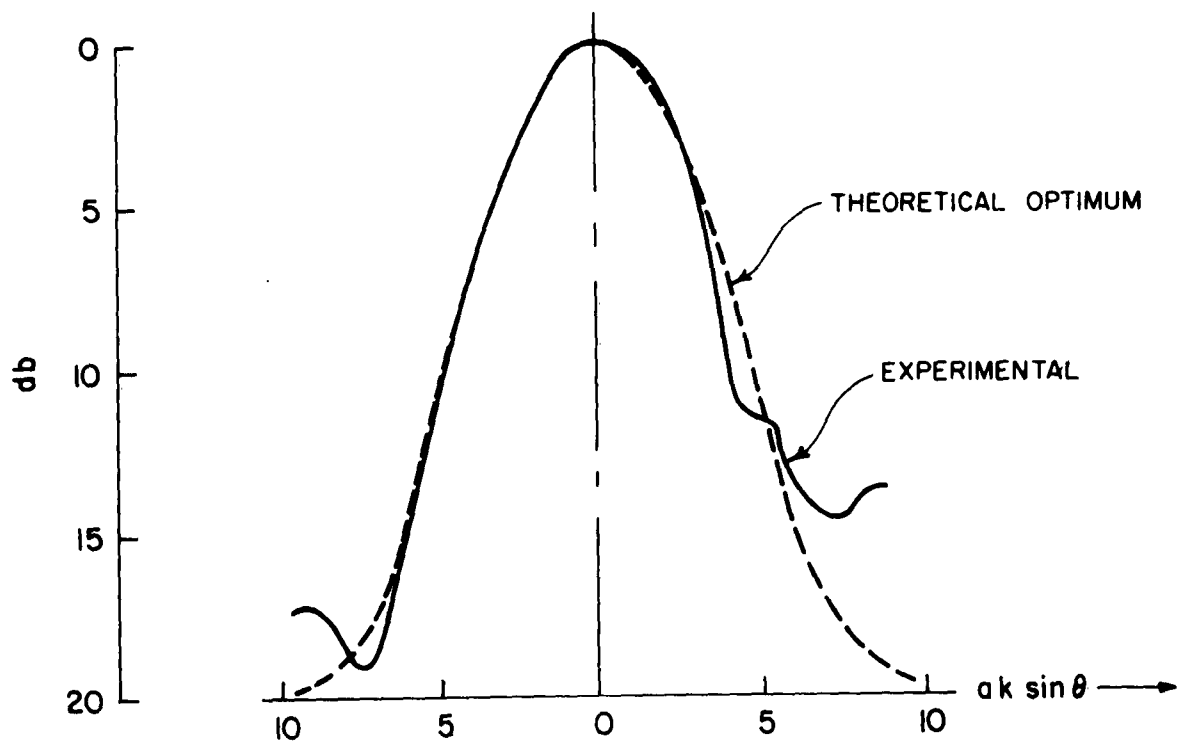
Figure 13.2b. Spiral Cerenkov Coupler - Vertical Polarization

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